FUEL ECONOMY AND GREENHOUSE GAS EMISSIONS LABELING AND STANDARDS FOR PLUG-IN ELECTRIC VEHICLES FROM A LIFE CYCLE PERSPECTIVE

by

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A thesis submitted
in partial fulfillment of the requirements
for the degree of
Master of Science
(Natural Resources and Environment)
in the University of Michigan
April 2013

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Abstract

Reflecting the greenhouse gas (GHG) emissions attributable to plug-in electric vehicles (PEV) on energy and emissions labels, and in vehicle GHG emissions regulations, is complex due to spatial and temporal variation in fueling sources and vehicle use. The relative environmental performance for conventional gasoline vehicles can be reflected by the fuel economy of the vehicle due to the strong correlation between fuel economy and vehicle life cycle emissions. However, this correlation does not hold for PEVs and a more comprehensive emissions accounting methodology needs to be utilized to evaluate their environmental performance.

This thesis is organized into two studies. The first evaluates PEV GHG emissions vehicle labeling and the effects of regional grids and regional daily vehicle miles traveled (VMT) on the total vehicle life cycle energy and GHG emissions. The model results indicate that only 25% of the life cycle emissions from a representative plug-in hybrid vehicle are reflected on current U.S. Environmental Protection Agency (EPA) vehicle labeling. Unexpectedly, for two regional grids the life cycle GHG emissions results were higher in electric mode than in gasoline mode. A recommendation is made that labels include stronger language on their deficiencies and provide ranges for GHG emissions from vehicle charging in regional electricity grids to better inform consumers.

The second study evaluates U.S. EPA's GHG emissions accounting methodology and current and future standards for new electrified vehicles. The current approach employed by the EPA is compared with an accounting mechanism where the actual regional sales of PEVs, and the regional electricity emission factor in the year sold, is used to determine the vehicle compliance value. The results showed that in the absence of a major policy shift, the small changes in the emission factors observed suggest that the complexity involved in tracking and accounting for regional PEV sales will not dramatically increase the effectiveness of the regulations to capture PEV electricity related GHG emissions.

Acknowledgements

The research in this thesis was conducted as part of the U.S.-China Clean Energy Research Center's (CERC) Clean Vehicle Consortium (CVC), which is partially supported by the U.S. Department of Energy [Award No. DE-PI0000012]. This research is Project 3 within Thrust 6: Energy Systems Analysis, Technology Roadmaps and Policy, of the CERC-CVC. This research was also funded through a National Science Foundation's Emerging Frontiers in Research and Innovation (EFRI) Resilient and Sustainable Infrastructures (RESIN) grant [Award No. 0835995].

I would like to thank my research advisors, Professor Keoleian and Dr. Kelly, for their guidance and insight through every stage of this research.

I would also like to acknowledge valuable feedback and contributions from Jeff Alson, Andrew Burnham, Kevin Bolon, Professor DeCicco, David Ganss, Aaron Hula, Jason MacDonald, Dawn Manley, Professor Miller, Tim Wallington, Candace Wheeler, and Professor Xu.

I received a lot of help and support from fellow CERC researchers at the University of Michigan, including Hua Cai, Joe Colett, and Anne Marie Lewis, and from other CERC member universities including Ingrid Akerlind, Dr. Du, and Professor Wang.

I would like to acknowledge Helaine Hunscher and Robb De Kleine at the Center for Sustainable Systems for helping with the logistics of my research.

A final thank you to my parents, my family, and Melissa who encouraged and supported me every step of the way.

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Nomenclature

Name	Symbol	Units
Upstream vs. combustion index	a	-
Fuel type	b	-
Vehicle class	c	-
Census area	C	-
Vehicle miles traveled	d	miles
Electricity generation	e	kWh
Total electricity consumption	E	kWh
Fuel economy	f	miles/gallon
Liquid fuel emission factor	g	gCO_2eq/gallon
Grid loss factor	h	-
Power plant index	i	-
North American Electric Reliability Corporation (NERC) sub-region	j	-
Grid loss region	k	-
Electricity generation percentage	l	-
Electricity GHG emissions	m	gCO_2eq
Electricity GHG emission factor	$\dot{m}$	gCO_2eq/kWh
Census region or division	n	-
Electricity generation fuel type	o	-
Share of flex fuel vehicle operating on E85 (85% Ethanol)	p	-
Vehicle sales	q	-
Vehicle emission rate	r	gCO_2eq/mile
Share of sales by vehicle class	S	-
Share of sales by vehicle class normalized	$\hat{S}$	-
Total GHG emissions	T	gCO_2eq
Utility factor	U	-
VISION model PHEV FE correction factor (Argonne National Laboratory 2012)	v	-
Vehicle production related emissions	V	gCO_2eq
Car and truck index	w	-
Vehicle weight	W	lbs.
Vehicle weight correction factor	$\hat{W}$	-
Vehicle type	x	-
Year	y	year

State index	z	-
Slope of GREET 2 correlation (Michael Wang, Burnham, and Wu 2012)	α	-
Intercept of GREET 2 correlation (Michael Wang, Burnham, and Wu 2012)	β	gCO_2eq/mile
Total regional electricity emission factor	ε	gCO_2eq/kWh
Vehicle sales scaling factor	λ	-
National average electricity emissions factor	μ	gCO_2eq/kWh
Total vehicle cycle emissions	σ	gCO_2eq

Forward

This thesis is organized into two studies. The first evaluates PEV GHG emissions vehicle labeling and the effects of regional grids and regional daily vehicle miles traveled (VMT) on the total vehicle life cycle energy and GHG emissions. The work from this first chapter of the thesis was published in the Journal of Industrial Ecology: MacPherson, N.D., G.A. Keoleian, and J.C. Kelly, "Fuel economy and greenhouse gas emissions labeling for plug-in hybrid vehicles from a life cycle perspective" *Journal of Industrial Ecology* (2012) 16(5): 761-773.

The second study evaluates U.S. EPA's GHG emissions accounting methodology and current and future standards for new electrified vehicles. The current approach employed by the EPA, using projected regional vehicle sales of PEVs to determine a national weighted GHG electricity emission factor, is compared with an accounting mechanism where the actual regional sales of PEVs and the regional electricity emission factor in the year sold, is used to determine the vehicle compliance value. The work and findings from chapter two will be submitted for publication.

Chapter 1: Greenhouse Gas Emission Labeling for PEVs

1.1 Introduction

Since 1977, the U.S. Environmental Protection Agency (EPA) has used fuel economy, in miles per gallon, as the metric for consumers to compare the energy efficiency of different new vehicles. With the overwhelming number of vehicles sold in the U.S. operating on a single petroleum fuel, either gasoline or diesel (U.S. Environmental Protection Agency 2011f), the fuel economy metric has been an effective indicator of vehicle efficiency, and more generally, the overall total vehicle life cycle greenhouse gas (GHG) emissions of the vehicle.[1] This chapter will demonstrate that while there is a strong correlation between fuel economy, life cycle energy and GHG emissions for conventional gasoline vehicles, the current fuel economy metric may not serve as an accurate indicator for electrified vehicles, which include pure battery electrics (EVs), plug-in hybrid electrics (PHEVs), and fuel cell vehicles.

1.1.1 Previous Life Cycle Modeling

Previous work by Argonne National Laboratory, which modeled PHEVs within various electric grids, has shown that the use phase GHG emissions from a PHEV can vary from 10% higher than a baseline conventional vehicle (CV) with an internal combustion engine on a grid dominated by coal, to 90% lower on a grid dominated by non-fossil electricity sources (Elgowainy et al. 2010). Samaras and Meisterling (2008) report life cycle PHEV GHG reductions, compared to grid independent hybrid electric vehicles (HEVs), between 30% and 47% on a low carbon grid and increases between 9% and 18% on a carbon intensive grid. Other studies have reported similar results when modeling PHEVs on low and high carbon grids (Jaramillo et al. 2009; Stephan and Sullivan 2008). Life cycle assessment (LCA) can be used to model energy and emissions, which occur during a vehicle's lifespan. LCA is not currently being utilized for evaluating standards for

[1] Note: The term 'total vehicle life cycle emissions' is defined as the emissions which occur over the lifetime of a vehicle and include all phases of the life cycle (including use phase, upstream, vehicle production and end of life (EOL)). The word 'total' is added to highlight the distinction between emissions from all life cycle stages and the vehicle production and EOL emissions, which are referred to in this thesis as 'vehicle cycle emissions'.

vehicles, for example U.S. Corporate Average Fuel Economy, CAFE, standards. Furthermore, total vehicle life cycle emissions are not reported on vehicle labels. In this thesis, a life cycle approach is used to explore the variation between the energy and GHG metrics used for U.S. EPA PHEV labeling on new model vehicles, and a more comprehensive accounting of the life cycle based GHG emissions of vehicles sold in the U.S. market. The life cycle model was selected to explore the gaps in accounting of PHEV GHG emissions because it includes all major inputs from well-to-wheel.

Although a life cycle approach is not currently being applied to vehicle fuel economy labeling, this approach has been utilized in recent regulations by the U.S. EPA in the transportation fueling sector, under the Renewable Fuel Standard (RFS) program (U.S. Environmental Protection Agency 2010b). The 2010 RFS program sets requirements for an annual fuel volume of biofuels that must be used in transportation fuels (U.S. Environmental Protection Agency 2010b). The RFS regulations require that the life cycle GHG emissions of a renewable fuel must be less than the 2005 baseline fuel it replaces (U.S. Environmental Protection Agency 2010b).

1.1.2 Labeling for Electrified Vehicles

In July 2011, the EPA released the final rule for revisions and additions to the U.S. vehicle fuel economy label. Figure 1 shows the current label design and vehicle information for a conventional gasoline vehicle and the new label for a PHEV. The revised label adds new information on fuel economy and GHG emissions for different vehicle technologies. For PHEVs, separate fuel economy values for both gasoline-only and electric/blended mode are provided on the label. On the new label, GHG emissions are primarily presented on a one to ten “goodness” scale relative to all new vehicles, but they are also presented as an absolute gCO_2 per mile value (U.S. Environmental Protection Agency 2011f). For PHEVs and EVs, the GHG emissions from electricity are reflected on the new label as zero, but consumers can explore how the regional differences in electricity factor into vehicle emissions by using the EPA’s fuel economy website, fueleconomy.gov (U.S. Environmental Protection Agency and U.S. Department of Transportation 2011, 39558).

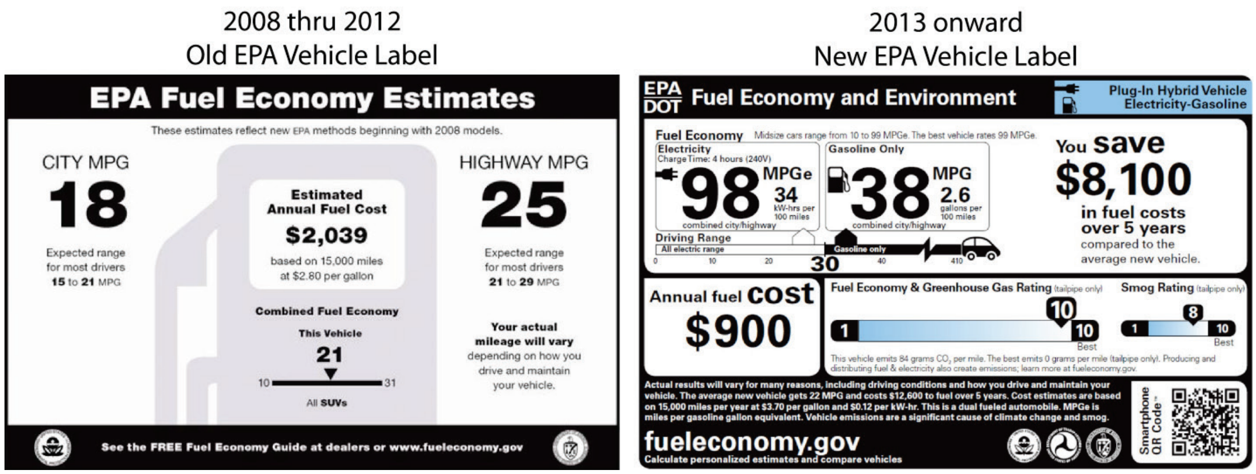


Figure 1 Environmental Protection Agency (EPA) fuel economy label comparison between old and new labels. Sources: U.S. EPA (U.S. Environmental Protection Agency 2010d; 2011f))

The life cycle burdens of vehicle production and end of life (EOL) are not accounted for on the label or on the fuel economy website; however, these components of the life cycle can be significant. For conventional petroleum powered vehicles, these life cycle stages account for approximately 10% of the total vehicle life cycle GHG emissions, and the vehicle production and EOL contributions for PHEVs and EVs can be even higher (A. Burnham, Wang, and Wu 2006). Furthermore, as fuel efficiency standards increase, automakers will increase their usage of energy intensive materials, such as aluminum, which research has shown may increase the production stage GHG emissions of the vehicle life cycle, depending on material sourcing, recycling rates, and the lifetime of the vehicle (Kim et al. 2010; Sullivan, Burnham, and Wang 2010; Geyer 2008).

Although the vehicle cycle (vehicle production and EOL) emissions were not included in the discussion of the *Revisions and Additions to Motor Vehicle Fuel Economy Label* (U.S.

Environmental Protection Agency and U.S. Department of Transportation 2011, 39478), the rationale behind the decision to not include the associated upstream emissions from electricity on the label was incorporated into the final rule. The EPA received comments from stakeholders on both sides on whether to include upstream emissions. The EPA recognized that upstream emissions information was relevant to consumers; but their inclusion on the physical label was not the best medium to present this information. The agency was concerned that including a single national average would confuse consumers aware of regional variation, but inclusion of regional variation would be both complex and costly to communicate. Instead the agency provided the following note regarding upstream emissions from electricity, "producing and distributing fuel & electricity also creates emissions; learn more at fueleconomy.gov" (U.S. Environmental Protection Agency and U.S. Department of Transportation 2011, 39492).

This study applies industrial ecology concepts and tools to evaluate the fuel economy label and its accuracy in characterizing the GHG emissions of PHEVs and EVs over the vehicle life cycle. Life cycle models are developed building upon previous LCA research on electrified vehicles. Argonne National Laboratory modeled PHEVs using different grid mixes (Elgowainy et al. 2010) and found large variations in vehicle CO_2 emissions between regions. Weber et al. (2010) conducted analysis on the uncertainty of regional emission factors and explored how life cycle assessment can utilize regional factors, while considering uncertain information and different levels of electric grid aggregation. He and Bandivadekar (2011) analyzed the relationship between vehicle standards and taxes, and vehicle carbon intensity. They found that many of the policies used by governments to influence vehicle carbon emissions did not correlate to incentivizing less carbon intensive vehicles. The analysis performed in this work highlights how differences in regional daily vehicle miles traveled (VMT) variations, spatial electric sector emission factors and vehicle production and EOL differences will influence the expected GHG emissions that are not reflected on either the EPA fuel economy label, on-line at the fueleconomy.gov web site, or both.

1.2 Methodology

Life cycle assessment is utilized to model and compare GHG emissions included and omitted from current and proposed labels of CVs, EVs, HEVs and PHEVs. LCA is the process of quantifying environmental emissions throughout a product's lifetime. LCA quantifies impacts from raw material acquisition to final product disposal (International Organization for Standardization 2006). A process-based life cycle model is used to evaluate both fuel cycle and vehicle cycle GHG emissions for each life cycle stage.

The main components of the PHEV life cycle model, shown in figure 2, include the fuel cycle, both electric and liquid, and the vehicle production and EOL cycle. The electric fueling component includes mining, processing and transportation of fuel to the power plant, generation of electricity at the power plant, and losses between the plant and the vehicle. The liquid fueling stage includes the extraction, processing and transportation of the fuel as well as combustion during the vehicle use phase. A utility factor used in the model characterizes the relative contribution of each electric and liquid fueling component. The utility factor indicates the fraction of miles driven in electric, or 'charge depleting mode', while one minus the utility factor represents the fraction of miles driven in gas, or 'charge sustaining', mode (Society of Automotive Engineers 2010). The vehicle cycle includes vehicle material extraction and production, vehicle component manufacturing, vehicle assembly and end of life vehicle disassembly and recycling (A. Burnham, Wang, and Wu 2006). Figure 2 also identifies the specific energy and emissions data reported on the label or on the EPA fuel economy website (U.S. Environmental Protection Agency 2011).

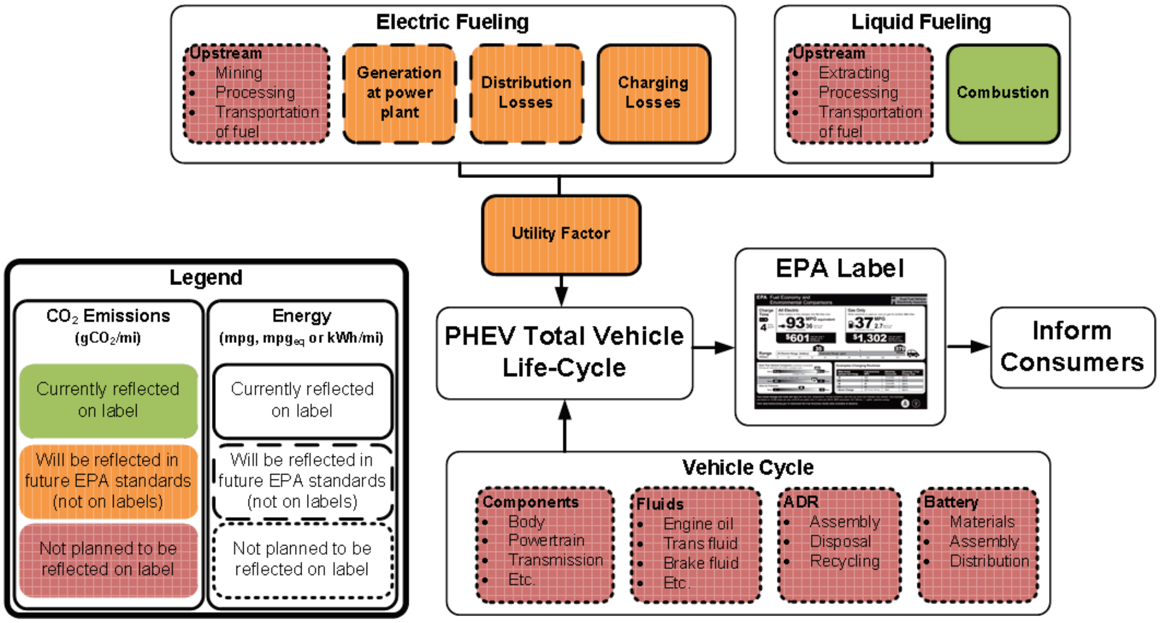


Figure 2 Layout of inputs to the plug-in hybrid vehicle (PHEV) total vehicle life cycle model. ADR = assembly, disposal, and recycling; EPA = Environmental Protection Agency; EV = electric vehicle; gCO_2/mi = grams of carbon dioxide per mile; kWh/mi = kilowatt-hours per mile; mpg = miles per gallon; mpg_{eq} = miles per gallon equivalent.

1.2.1 Electricity: Upstream and Generation

Power plant energy and emissions data published by the EPA were utilized to model the electrical fueling component in the PHEV total vehicle life cycle model. The eGrid2010 database reports average emissions and energy data for years 2004, 2005 and 2007, the later used in this analysis. The EPA eGrid2010 database was used because it reports emissions and energy on a nationwide, region, sub-region and state level, including the District of Columbia (U.S. Environmental Protection Agency 2011a). The sub-regions are divided based on power plant affiliation within a North American Reliability Corporation (NERC) area. NERC regions and NERC sub-regions are based on power company control rather than physical location, which means that the boundaries to these regions are not bound by state lines (U.S. Environmental Protection Agency 2010a).

For the upstream electric energy and emissions portion of the total vehicle life cycle model, the U.S. Life cycle Inventory (USLCI) database was utilized to determine values

(National Renewable Energy Laboratory 2008)[2]. The USLCI database was chosen because of its disaggregation of emission factors for each fuel type. For instance, the USLCI database contains separate emission factors for specific types of coal instead of one combined value. This is relevant since the eGrid database reports the specific primary fuel used (e.g., residual fuel oil, biomass, bituminous coal) at each power plant, not just the category (e.g., oil, renewable, coal). To achieve a more accurate upstream emission factor for each electric generation region the specific fuel type was used. Upstream processes include mining, extracting and transporting of the fuel to the electric generation plant. (Table A3 in appendix A contains all of the upstream emission factors used in the model.)

The CO_2eq calculations are based on emissions from CO_2, CH_4 and N_2O and Intergovernmental Panel on Climate Change 100 year global warming potentials used to convert emissions into CO_2 equivalency (Forster et al. 2007, 212). An electricity emission rate (ε_{aj}), in grams of CO_2eq per kWh, is found for both upstream (*a*=1) and plant generation (*a*=2) emission sources within different regions (*j*). The three types of electric grid regions explored in this paper are NERC regions, NERC sub-regions, and states.

$$\varepsilon_{1j} = \frac{\frac{\sum_{i=1}^{I} \dot{m}_{1b} * e_i}{\sum_{i=1}^{I} e_i}}{1 - h_k} \quad \forall\, k, b \in j \qquad (1)$$

The eGrid database was used to find annual heat input, annual generation, combustion energy, and emission factors for each power plant in the U.S. (U.S. Environmental Protection Agency 2011a). The emission rate calculation for upstream, equation 1, was found by multiplying the upstream emission rate ($\dot{m}_b$), in grams of CO_2eq per kWh or

[2] Note: Upstream electricity emission factors are currently being evaluated and updated due to recent changes in the production and extraction methods used for fuels such as natural gas (U.S. Environmental Protection Agency 2011b; Andrew Burnham et al. 2012). The upstream USLCI factors applied here, and listed in table A3 in appendix A, do not reflect these new emission evaluations.

grams of CO_2eq per Btu, by the plant generation or plant input energy (*e*), in kWh or Btu respectively, for each plant (*i*). The total emissions were then divided by the total generation for the region or state, in kWh, where the subscript *b* in equation 1 represents the power plant fuel type.

$$\varepsilon_{2j} = \frac{\frac{\sum_{i=1}^{I} m_{2i}}{\sum_{i=1}^{I} e_i}}{1 - h_k} \;\forall\, k \in j \qquad 2$$

The plant generation emissions rate, shown in equation 2, was found by summing the CO_2eq emissions (*m*), from each plant (*i*) and dividing by the sum of the plant electricity generation (*e*), in kWh. To account for the transmission and distribution losses, which occur between the plant and the charging location, the emission and generation rate is divided by ($1-h_k$), where h_k is the 'Grid Loss Factor' from eGrid and is applied for five different regions of the U.S. The subscript *k* in the 'Grid Loss Factor' variable, represents each of the five regions (Eastern, Western, Texas, Alaska and Hawaii, see table A1 in appendix A for region and national average values (U.S. Environmental Protection Agency 2010a)).

The emission rates for upstream and generation are multiplied by the EPA-published electric fuel consumption (f_1), in kWh per mile, of the vehicle in electric mode, which puts vehicle emissions in terms of grams per mile (r_{EVaj}).

$$r_{EVaj} = f_1 * \varepsilon_{aj} \qquad 3$$

This vehicle emission rate on a per mile basis, shown in equation 3, allows for a direct comparison between the calculated total vehicle life cycle model emission values and the emissions included on EPA labels (U.S. Environmental Protection Agency 2011f). The subscript *j* again represents an index for each electric grid region from the state to NERC region level. This electric emissions rate is combined with the liquid emissions rate and vehicle cycle rate, calculated in the next sections, to produce the total vehicle life cycle emissions per mile.

1.2.2 Liquid (Gasoline): Upstream and Combustion

The emission factors for the gasoline fuel cycle (g_a) were taken directly from the Greenhouse Gases, Regulated Emissions and Energy Use in Transportation (GREET) 1.8d database, published by Argonne National Laboratory (M. Wang 2010). (The values for gasoline upstream and combustion emission rates are summarized in table A4 in appendix A.)

$$r_{Ga} = \frac{1}{f_2} * g_a \qquad (4)$$

The upstream emission rate (a=1), in grams CO_2eq per gallon, includes extraction, refining and distribution of the fuel. The combustion emission rate (a=2), in grams CO_2eq per gallon, represents point source emissions from the vehicle. The EPA-published combined fuel economy (f_2), 45% highway and 55% city harmonic weighting, is converted to fuel consumption, in gal per mile, (U.S. Environmental Protection Agency 2011f) and multiplied by the emission rates associated with gasoline from GREET (M. Wang 2010). This results in the GHG emissions per mile for the 'gas only' mode (r_{Ga}), shown in equation 4.

1.2.3 Vehicle Cycle

The vehicle cycle (σ) includes vehicle components (V_1), assembly, disposal and recycling (V_2), battery (V_3), and fluids (V_4). Vehicle weights were utilized to find the production and EOL burdens for each vehicle in the GREET 2.7 database (A. Burnham, Wang, and Wu 2006). A correlation exists in the GREET 2.7 vehicle cycle model between vehicle weights and vehicle cycle related emissions.

Vehicle weights for each 2011 model year vehicle sold within the U.S. were extracted from the U.S. EPA *Test Car List Data* for 2011 (2011c). All vehicle cycle data were taken directly from the GREET model, except for life cycle battery data, which was extracted from a recent Argonne National Laboratory report of current battery technology (Sullivan and Gaines 2010). Although the EPA lists vehicle weights for every vehicle they test, they do not publish the weight of the battery pack. The weights of the battery for the electrified vehicles modeled were found from industry published specifications for each vehicle and academic studies which utilize the battery weights of the electrified vehicles (General Motors 2011; Nissan 2011; Faria et al. 2012). Furthermore, GREET 2.7 does not include a specific modeling scenario for pure electric vehicles or PHEVs. For the PHEV, the conventional hybrid vehicle scenario was used in GREET but the sizing of the battery pack was changed. In order to model pure EVs Argonne National Laboratory advised that the fuel cell scenario included in the GREET database was very similar to a pure EV. They recommended the modification of the fuel cell scenario in GREET by removing the fuel cell stack materials and adding, in its place, the EV battery model as described above (A. Burnham 2011).

$$\sigma = \frac{\sum_{i=1}^{4} V_i}{d} \tag{5}$$

A vehicle lifetime (*d*) of 160,000 miles was chosen based on the GREET default values (A. Burnham, Wang, and Wu 2006). This lifetime is similar to the value published in a study by the National Highway Traffic Safety Administration and vehicle lifetimes used in other vehicle life cycle modeling research (U.S. Department of Transportation 2006; Samaras and Meisterling 2008; Stephan and Sullivan 2008). The vehicle lifetime is used in equation 5 to calculate the resulting vehicle production and EOL component of the total vehicle life cycle emissions.

1.2.4 Total Vehicle Life Cycle Calculation

The fuel cycle results were combined with the vehicle cycle results to find the total vehicle life cycle emissions (*T*) on a per mile basis for each vehicle listed in the EPA test data.

$$T_j = \left(\left(r_{EV1j} + r_{EV2j}\right) * U\right) + \left(\left(r_{G1} + r_{G2}\right) * (1 - U)\right) + \sigma \qquad 6$$

For electrified vehicles, the term *T* is found for each NERC region, NERC sub-region or state, *j*. To find the total vehicle life cycle emissions for PHEVs, a utility factor (*U*) is used in equation 6 to indicate what percentage of the time the PHEV is utilizing electric mode only. The utility factor used for modeling the Chevrolet Volt PHEV was 0.635, which is consistent with the EPA's utility factor used for the label. The 0.635 utility factor indicates that 63.5% of the miles driven are in electric mode. The utility factor varies with the PHEVs all-electric range (AER) (Society of Automotive Engineers 2010). Intuitively, a longer AER means a greater share of the miles driven will be in electric mode leading to a higher utility factor. The utility factor applied for modeling the Volt is for a PHEV with an AER of 35 miles (U.S. Environmental Protection Agency 2011b).

In order to further explore regional electrified vehicle variation, specific utility factors for each NERC region were used. These region specific utility factors were calculated from actual daily VMT data from the National Household Travel Survey database (NHTS) (U.S. Department of Transportation 2011) grouped by region and simulated for the Volt characteristics using the methods of analyzing the NHTS data described in Kelly, et al. (2012). One aspect, which is not included here, is any changes in the actual driving patterns of the individuals in these different regions. The utility factor can be tailored to represent city versus highway driving, however the regional factors used here are not taking into account any driving intensity differences, only the miles traveled by the vehicles in that region. The calculated aggregate national utility factor, found by averaging each of the regionally found utility factors was 0.602, which is slightly less than the EPA utilized value. This can be attributed to a few factors including the use of cut offs for data deemed unrealistic. For example, any vehicle traveling at a speed greater than 120 miles per hour was omitted from the regional utility factor calculations. Additionally any vehicle trip longer than 1,920 miles is omitted since it is equivalent to a vehicle traveling at an average 80 miles per hour over a 24-hour period.

1.3 Results and Discussion

1.3.1 The Relationship between Fuel Economy and GHG Emissions

To determine if the metric of fuel economy is indicative of vehicle GHG emissions the relationship between the label fuel economy and the total vehicle life cycle emissions is evaluated. Figure 3 shows the correlation between the vehicle fuel consumption (the inverse of fuel economy) and the total vehicle life cycle GHG emissions of all the vehicles tested by the EPA for fuel economy labeling purposes. Fuel consumption, rather than fuel economy, was used due to its linear correlation (U.S. Environmental Protection Agency 2011f, 7). Figure 3 allows for a comparison between the spatial variation of emissions from PHEVs and EVs and the life cycle emission characteristics of CVs. The ranges shown on the figure for the Chevrolet Volt PHEV and the Nissan Leaf EV indicate the highest and lowest total vehicle life cycle emissions in the states with the highest and lowest, the District of Columbia and Vermont respectively, electric GHG intensity. The figure shows that life cycle GHG emissions are closely related to fuel consumption, and by the inverse, to fuel economy. The strong correlation between the vehicle life cycle emissions and fuel economy shows that the fuel economy metric has been a strong indicator of environmental life cycle performance for conventional vehicles. However, for PHEVs and EVs, the figure suggests that there are large variations not taken into account by a single fuel economy metric.

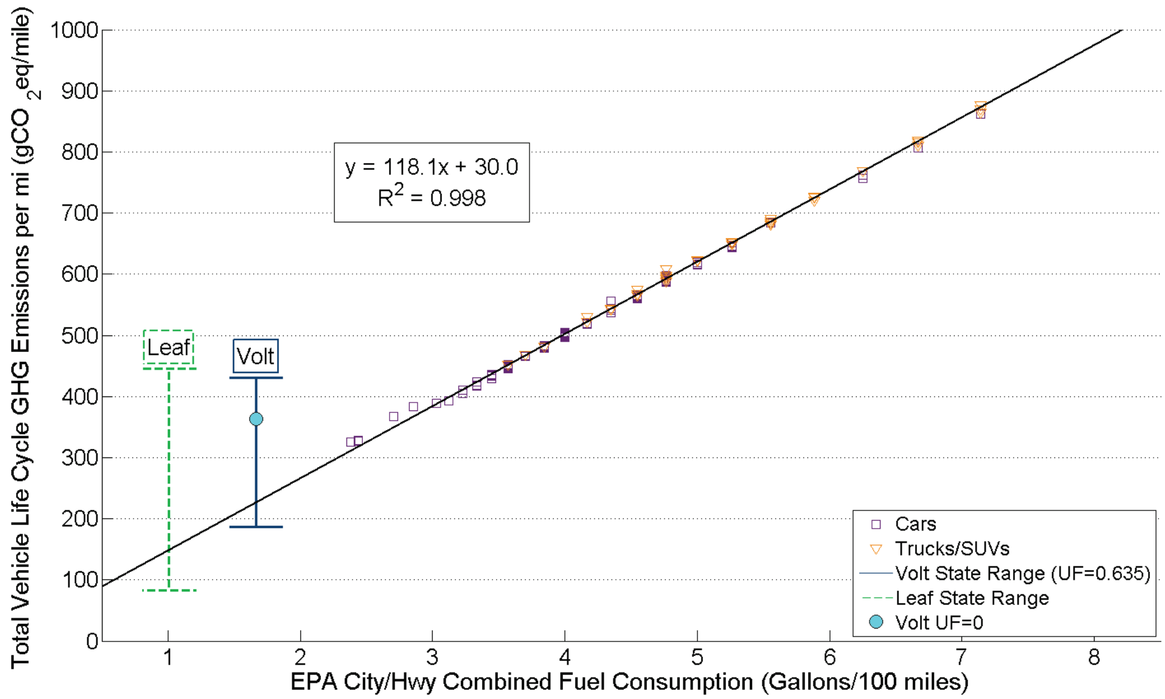


Figure 3 Total vehicle life cycle greenhouse gas (GHG) emissions per mile versus EPA city/highway combined fuel consumption metric, for all vehicles tested by the EPA for labeling purposes. Passenger classified vehicles are denoted by open square markers while sport utility vehicles (SUVs) and trucks have open triangle markers. The range of GHG emissions between the highest and lowest state electric grid carbon intensity, for the Nissan Leaf and Chevrolet Volt, is shown on the left side of the graph. The range for the Volt is shown assuming a 0.635 utility factor (UF) for both high and low bar. The filled circular marker in the Volt range indicates the total vehicle life cycle GHG emissions per mile for a vehicle utilizing only 'gas mode'. EPA = Environmental Protection Agency; gCO_2eq/mile = grams of carbon dioxide equivalent per mile; Hwy = highway.

1.3.2 GHG Emissions Reflected on Vehicle Labels

Fuel economy labels for PHEVs presently report only the emissions from the vehicle's tailpipe. The reporting differences between the current label and the life cycle emissions from the model used in this article are shown in figure 4.

		gCO_2/mile	gCO_2eq/mile
		2012 EPA label	*Life Cycle Model (U.S. Average Grid)*
2011 Chevy Volt (UF=0.635)	Gasoline 'Tailpipe'	84	*91*
	Gasoline Upstream	21 (Online only)	*19*
	Electricity Generation	138 (Online only)	*144*
	Electricity Upstream	9 (Online only)	*7*
	Vehicle Cycle	X	*69*
	Total	**84 (Label)/ 260(Online)**	***330***
Reference Vehicles	HEV (2011 Prius)	176 (Tailpipe only)	*281*
	ICV (2011 Camry I-4 Auto)	339 (Tailpipe only)	*486*

Table Legend
Reflected on label
Available at fueleconomy.gov only
Not reflected on label or online
Life Cycle model values

Figure 4 Comparison between what parts of the total vehicle life cycle are reflected on the 2012 "new" U.S. Environmental Protection Agency (EPA) label and the life cycle model values calculated in this article for the Chevrolet Volt. Variations between the EPA values, from the fueleconomy.gov site (U.S. Department of Energy and U.S. Environmental Protection Agency 2012) and the life cycle model values can be attributed to 1) The total life cycle model taking into account GHG impacts from methane and nitrous oxide, in addition to carbon dioxide, while the EPA values are in terms of carbon dioxide only. 2) Sources for upstream energy and emissions may differ. See table A4 in appendix A for a comparison to EPA values used for gasoline emission factors. Auto = automatic transmission; EPA = Environmental Protection Agency; gCO_2/mile = grams of carbon dioxide per mile; gCO_2eq/mile = grams of carbon dioxide equivalent per mile; HEV = hybrid electric vehicle; I-4 = inline-four cylinder engine; ICV = internal combustion engine vehicle; N/A = not applicable; UF = utility factor.

For comparison, the life cycle emissions from a conventional gasoline vehicle, a non-hybrid four cylinder 2011 Toyota Camry with an automatic transmission, and a popular grid independent hybrid, a 2011 Toyota Prius, are shown in figure 4 in addition to the 2011 Chevrolet Volt. The comparison vehicles were chosen due to both high sales volume and because they are in the same EPA vehicle class as the Volt (U.S. Environmental Protection Agency 2011c; M. Wang 2007). The three vehicles belong to the EPA midsize class, which is based on combined interior passenger and vehicle cargo volumes (U.S. Environmental Protection Agency 2011d). The tailpipe EPA label GHG emission values for the Camry and Prius are derived from their EPA estimated combined fuel economies (U.S. Environmental Protection Agency 2011c). The online values included in the table for the Volt are available for consumers to download from the EPA's Fuel Economy website and are based on the EPA's national averages for electricity generation emissions and the upstream emissions for gasoline. The table shows that there is almost a 4:1 difference between the tailpipe emissions reflected on the label for the Volt, 84 grams CO_2 per mile, and the total vehicle life cycle emissions, 330 grams CO_2eq per mile.

1.3.3 Electricity Grid Regional Variation

The values shown in figure 4 represent differences between the EPA label and the total vehicle life cycle results; however, other issues of emission variation arise when exploring regional and state level electric grids. For instance, the state life cycle GHG emission ranges for the Volt and Leaf, shown in figure 3, do not take into account the electricity imports and exports that occur between states and NERC sub-regions. There are ten states that import 25% or more of their electricity from surrounding states and regions (U.S. Environmental Protection Agency 2011a; Marriott and Matthews 2005). For high import or high export states, the state calculated emission factors are not good indicators of vehicle life cycle emissions when analyzing at these smaller electric grid areas.

Since state lines do not bind NERC regions, states can also belong to multiple NERC regions and NERC sub-regions shown in figure 5. Figure 6 contains emission factors for each state and NERC sub-region within the Western Electricity Coordinating Council (WECC) NERC region. As an example, the State of California, with a total vehicle life cycle emission factor (EF) of 245 gCO_2eq per mile, belongs to three different NERC sub-regions, which have EFs ranging from 258 to 321 gCO_2eq per mile, and is part of the wider WECC NERC region with an EF of 291 gCO_2eq per mile. Furthermore, within the NWPP sub-region, there is a greater than two-fold difference between the state with the lowest EF (Idaho) and the highest EF (North Dakota). It is difficult to apply one emission factor to a state or region due to this accounting variation at different grid levels, in addition to the issue of state and sub-region electricity imports and exports.

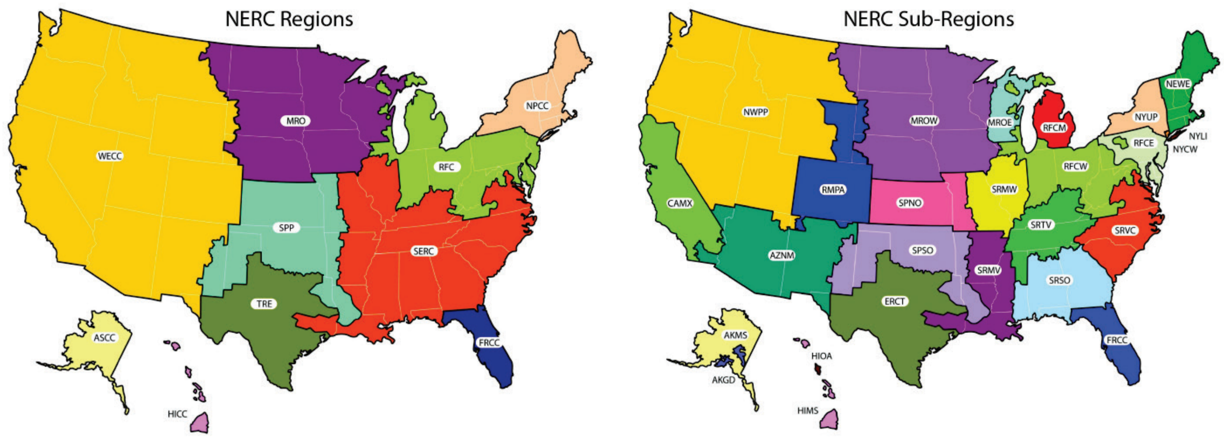


Figure 5 Geographical representation of North American Reliability Corporation (NERC) and NERC sub-regions. Source: U.S. Environmental Protection Agency eGird Technical Support Document (2010a). ASCC = Alaska Systems Coordinating Council; FRCC = Florida Reliability Coordinating Council; HICC = Hawaiian Islands Coordinating Council; MRO = Midwest Reliability Organization; NPCC = Northeast Power Coordinating Council; RFC = Reliability First Corporation; SERC = SERC Reliability Corporation; SPP = Southwest Power Pool; TRE = Texas Regional Entity; WECC = Western Electricity Coordinating Council; AKGD = ASCC Alaska Grid; AKMS = ASCC Miscellaneous; AZNM = WECC Southwest; CAMX = WECC California; ERCT = ERCOT All; HIMS = HICC Miscellaneous; HIOA = HICC Oahu; MROE = MRO East; MROW = MRO West; NEWE = NPCC New England; NWPP = WECC Northwest; NYCW = NPCC NYC/Westchester; NYLI = NPCC Long Island; NYUP = Upstate New York; RFCE = RFC East; RFCM = RFC Michigan; RFCW = RFC West; RMPA = WECC Rockies; SPNO = SPP North; SPSO = SPP South; SRMV = SERC Mississippi Valley; SRMW = SERC Midwest; SRSO = SERC South; SRTV = SERC Tennessee Valley; SRVC = SERC Virginia/Carolina.

<table>
<tr><th>NERC Region</th><th colspan="28">WECC</th></tr>
<tr><td>gCO_2eq/mile</td><td colspan="28">291</td></tr>
<tr><th>NERC Sub-Region</th><th colspan="7">AZNM</th><th>CAMX</th><th colspan="12">NWPP</th><th colspan="8">RMPA</th></tr>
<tr><td>gCO_2eq/mile</td><td colspan="7">321</td><td>258</td><td colspan="12">275</td><td colspan="8">394</td></tr>
<tr><th>State</th><th>AZ</th><th>CA</th><th>CO</th><th>NV</th><th>NM</th><th>OK</th><th>TX</th><th>CA</th><th>AZ</th><th>CA</th><th>CO</th><th>ID</th><th>MT</th><th>NV</th><th>NM</th><th>ND</th><th>OR</th><th>UT</th><th>WA</th><th>WY</th><th>AZ</th><th>CO</th><th>MT</th><th>NE</th><th>NM</th><th>SD</th><th>UT</th><th>WY</th></tr>
<tr><td>gCO_2eq/mile</td><td>313</td><td>245</td><td>383</td><td>313</td><td>381</td><td>351</td><td>331</td><td>245</td><td>313</td><td>245</td><td>383</td><td>193</td><td>359</td><td>313</td><td>381</td><td>435</td><td>225</td><td>397</td><td>207</td><td>430</td><td>313</td><td>383</td><td>359</td><td>342</td><td>381</td><td>319</td><td>397</td><td>430</td></tr>
</table>

Figure 6 Total vehicle life cycle emissions for the Western Electricity Coordinating Council (WECC) North American Reliability Corporation (NERC) region, NERC sub-regions within the WECC NERC and the greenhouse gas (GHG) emissions profile for states within each NERC sub-region, for the Volt at a 0.635 utility factor AZNM = WECC Southwest; CAMX = WECC California; NWPP = WECC Northwest; RMPA = WECC Rockies; AZ = Arizona; CA = California; CO = Colorado; NV = Nevada; NM = New Mexico; OK = Oklahoma; TX = Texas; ID = Idaho; MT = Montana; ND = North Dakota; OR = Oregon; UT = Utah; WA = Washington; WY = Wyoming; NE = Nebraska; SD = South Dakota; gCO_2eq/mile = grams of carbon dioxide equivalent per mile.

The WECC is not the only NERC region that has smaller electric region or state entities with a considerable range in the electricity emission factors. Figure 7 shows the emission factor ranges for the NERC sub-regions and states within each of the ten NERC regions. The WECC NERC region is the largest by area and there are ten states which are entirely part of the region and two which are only partially (those two states are not reflected in the figure since the majority of plants in the region are within a different NERC region). It is not surprising then that it is this region that has the greatest variation in emission factors between the encompassed states and between the NERC sub-regions. The Midwest Reliability Organization (MRO), Northeast Power Coordinating Council (NPCC), Reliability First Corporation (RFC), and SERC Reliability Corporation (SERC) regions are smaller than the WECC but also include substantial variation between the states within the region. The life cycle performance of the Volt varies by over 100 gCO_2eq per mile, between the highest and lowest carbon intensity states, within those four NERC regions.

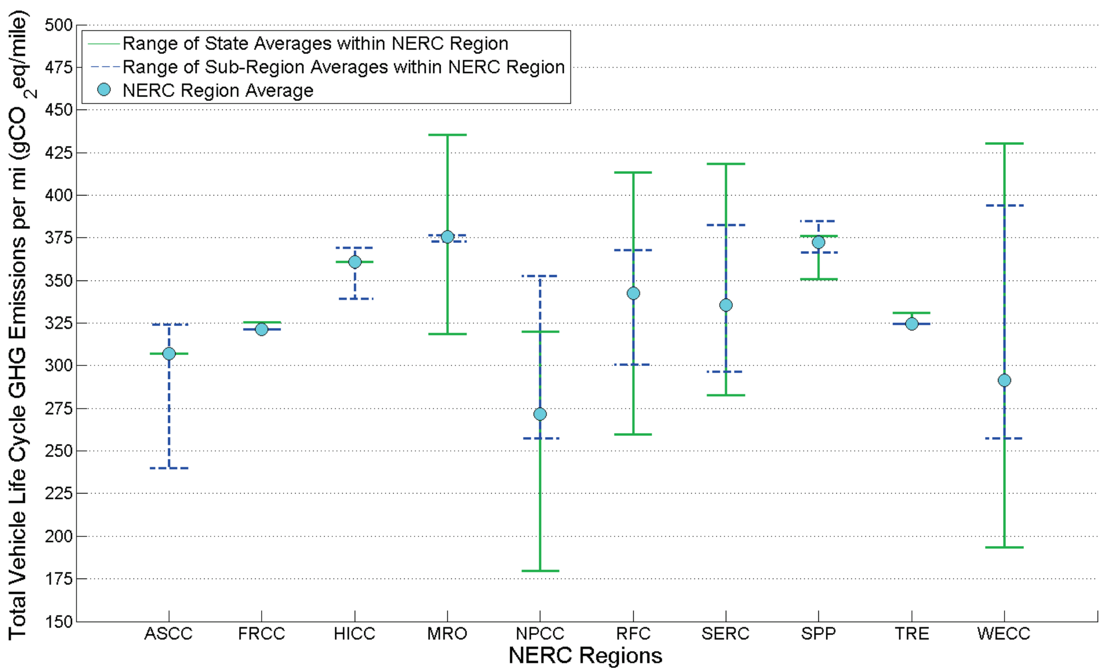


Figure 7 The range of total vehicle life cycle emissions, in grams CO_2eq per mile, is plotted for North American Reliability Corporation (NERC) sub-regions and states within each of the ten NERC regions. The dot in the range represents the average for that NERC region. The emission data is for the 2011 Chevrolet Volt PHEV using a 0.635 UF. ASCC = Alaska Systems Coordinating Council; FRCC = Florida Reliability Coordinating Council; HICC = Hawaiian Islands Coordinating Council; MRO = Midwest Reliability Organization; NPCC = Northeast Power Coordinating Council; RFC = Reliability First Corporation; SERC = SERC Reliability Corporation; SPP = Southwest Power Pool; TRE = Texas Regional Entity; WECC = Western Electricity Coordinating Council; gCO_2eq/mile = grams of carbon dioxide equivalent per mile; GHG = greenhouse gas; PHEV = plug-in hybrid vehicle; UF= utility factor.

The NERC sub-region variation is lower than the state variation for the majority of the NERC regions. Most sub-regions are larger than a single state, which means that much of the variation exhibited at the state level is masked by the larger, more aggregated, sub-region areas. Further, this aggregation means that for the majority of the NERC regions the sub-region variation is contained within the state variation. There are a few exceptions to this trend, where the sub-regions encompass areas smaller than a state. The NPCC NERC region for instance demonstrates that the sub-region emission rates could actually be higher than the state variation. In this particular case, the sub-regions part of the State of New York account for the range of life cycle emission rates within the NPCC NERC region. The Upstate New York (NYUP) and the small, by area, New York Long Island (NYLI) sub-regions are both higher than the highest and lowest states within the NPCC, Massachusetts and Vermont.

The Alaska Systems Coordinating Council (ASCC), Florida Reliability Coordinating Council (FRCC), Hawaiian Islands Coordinating Council (HICC), and Texas Regional Entity (TRE) are unique in that their NERC regions are either wholly contained within the state or are representative of the entire state. Due to their geography, Alaska and Hawaii are unique in that their associated NERC region boundaries are essentially the same as their state boundaries. The sub-region variation reflected in the figure is representative of two different eGRID classifications. The main grids within each of these states are assigned a to a sub-region while any generation utility which is not part of the main grid infrastructure is labeled as miscellaneous (U.S. Environmental Protection Agency 2010a). These miscellaneous NERC sub-regions have lower emission factors than the main grids but also account for less of the electricity generated at 30% of Alaska's total, for the ASCC Miscellaneous, and 32% of Hawaii's total, for the HICC Miscellaneous (U.S. Environmental Protection Agency 2011a). For the States of Florida and Texas, the NERC regions FRCC and TRE are contained within the state but there are other plants located within the state boundaries, which are part of other neighboring NERC regions. These other electricity plants must have higher GHG emission factors on average, than the NERC regions contained within the state, since the state level results are slightly higher. There is no sub-region variation reflected on figure 7 for the FRCC and TRE since these NERC regions are not broken down into any smaller aggregation areas.

The NERC region aggregation level of electric sector GHG emissions represents a more concrete measure of spatial variation for PHEVs than the state electric sector GHG emission level, since the interactions and electricity trading between NERC regions are less. Figure 8 shows the total vehicle life cycle variation for each of the ten NERC regions of the U.S. The GHG variations are plotted against the vehicle’s utility factor from zero, gas mode only, to one, electric mode only. Also included on this figure, marked by a different symbol for each line, is the average utility factor calculated for each NERC region based on driving patterns from the NHTS. The EPA utilized utility factor of 0.635 is shown on the figure as a vertical dashed line. The national average of the regional UFs is slightly less, at 0.602, than the EPA 0.635 value, as was mentioned in the methodology section. The figure shows that at a UF of 0.635, there is a variation of over 100 grams CO_2eq per mile between the lowest and highest NERC regions.

The figure also highlights how regional daily VMT differences can change the vehicle’s GHG emissions relative to the average utility factor used for labeling. For instance, the MRO and Southwest Power Pool (SPP) regions have higher life cycle GHG emissions in electric mode than gas mode. However, the regional VMT difference suggests that drivers in these regions, on average, utilize the gas mode of the PHEV more of the time than at the EPA utility factor. The regional utility factor in these two regions suggests that the life cycle GHG emissions from this representative PHEV would actually be less than the emissions predicted by the EPA utilized utility factor.

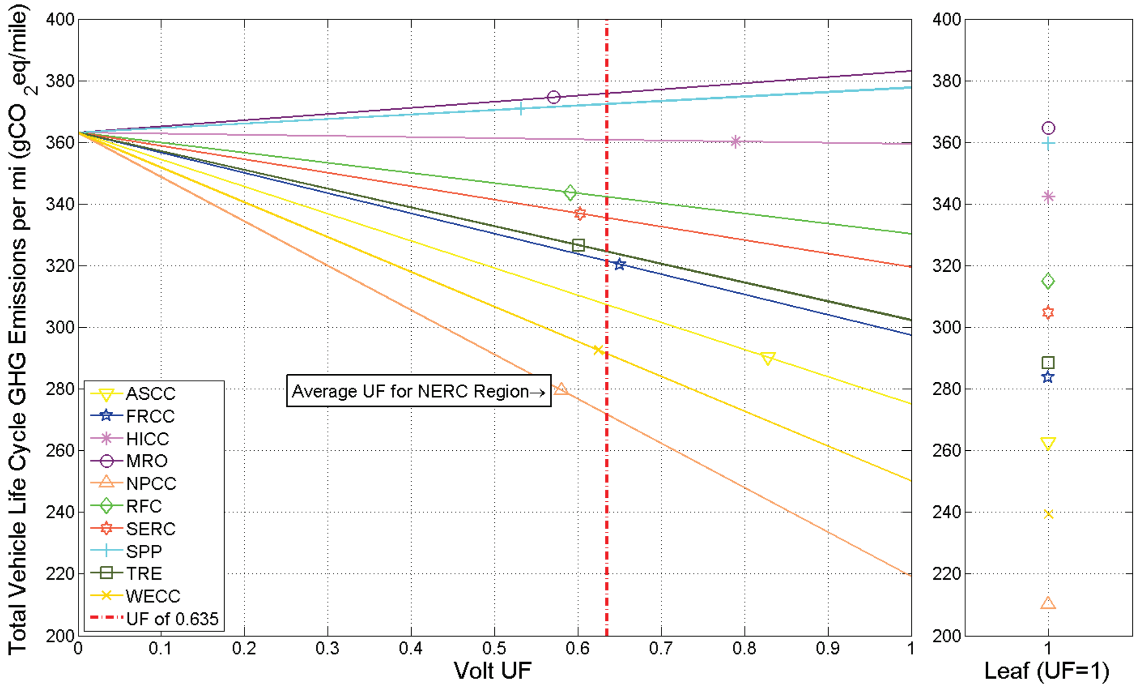


Figure 8 Total vehicle life cycle greenhouse gas (GHG) emissions per mile versus Chevrolet Volt utility factor (UF), for each of the ten North American Reliability Corporation (NERC) regions. A marker highlights the average UF for each NERC region. The dashed vertical line emphasizes the UF associated with a 35 mile all electric range vehicle. The sub-plot on the right shows the total vehicle life cycle GHG emissions per mile for the Nissan Leaf for each NERC region. It is important when interpreting this graph to recognize these two vehicles are not comparable if vehicle range is considered. The U.S. Environmental Protection Agency (EPA) evaluated the Volt to have an estimated range of 310 miles in gasoline mode, in addition to the 35 miles of rated all electric range, and that it will take 4 hours (at 240 volts) to charge the battery (U.S. Environmental Protection Agency and U.S. Department of Energy 2012a). The EPA estimates the Leaf can travel 73 miles on a charge and that it will take 7 hours (at 240 volts) to charge the battery (U.S. Environmental Protection Agency and U.S. Department of Energy 2012b). ASCC = Alaska Systems Coordinating Council; FRCC = Florida Reliability Coordinating Council; HICC = Hawaiian Islands Coordinating Council; MRO = Midwest Reliability Organization; NPCC = Northeast Power Coordinating Council; RFC = Reliability First Corporation; SERC = SERC Reliability Corporation; SPP = Southwest Power Pool; TRE = Texas Regional Entity; WECC = Western Electricity Coordinating Council; gCO_2eq/mile = grams of carbon dioxide equivalent per mile.

The majority of the regions showed a decrease in the PHEV utility factor compared to the label value. However, the ASCC, HICC, and to a lesser extent the FRCC, all showed higher utilization of electric only mode leading to smaller total vehicle life cycle emissions than would be reported using the current label value. These regional utility factors could have implications for the presentation of combined gas and electric mode for consumer labels or online. The EPA already allows customization of driving patterns online for the percentage of highway and city driving (U.S. Department of Energy and

U.S. Environmental Protection Agency 2012). Allowing consumers the ability to either select their own utility factor, or by showing the regional information, would allow for consumers to be more aware of the overall vehicle GHG emission profile depending on the mix of the two fuel sources (gas and electric).

Figure 9 shows the components of the life cycle emissions for the Volt in each of the NERC regions, using a UF of 0.635. The three stacked bars on the right are included to show the breakdown of the emissions for the Volt in charge sustaining mode and charge depleting mode in NERC regions with the highest and lowest EFs (MRO and NPCC). Since the life cycle performance varies based on the NERC region and the UF, the relative contribution of the vehicle production related emissions change significantly based on the different vehicle operational factors. At the UF of 0.635 the vehicle production emissions make up between 18.4% and 25.5% of the total life cycle emissions per mile, with the range increasing to 18.1% and 31.6% at a UF of one. The vehicle production makes up 19% of the total emissions when the vehicle is only operating in the charge sustaining mode (where the UF equals zero).

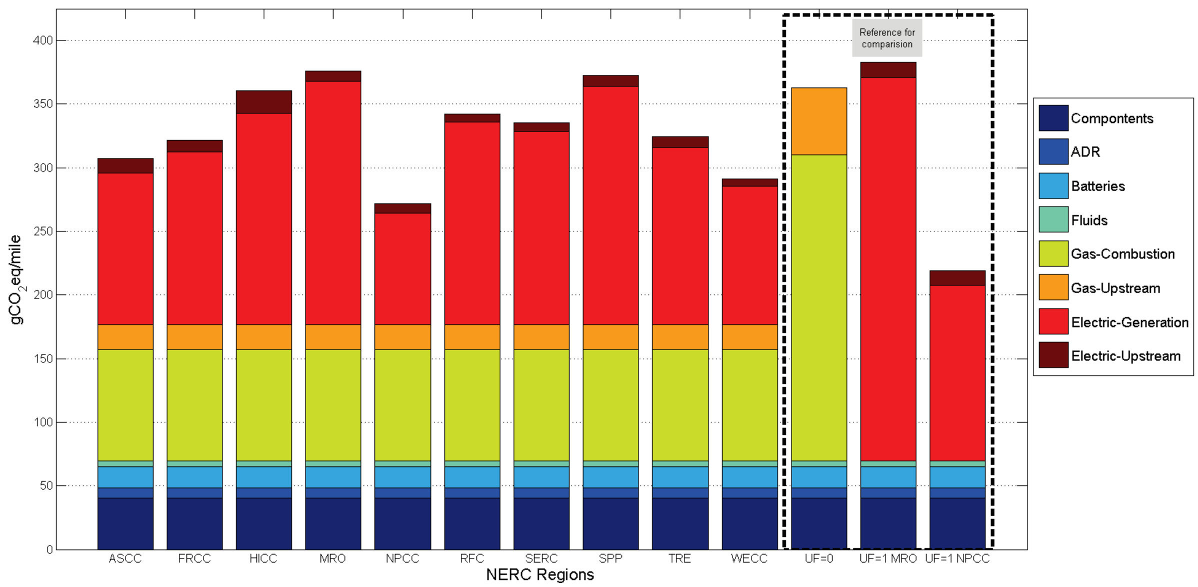


Figure 9 Composition of the total vehicle life cycle CO_2eq emissions per mile for each North American Reliability Corporation (NERC) region. A utility factor of 0.635 is used for each NERC bar. The reference bars, in the dashed box on the right of the graph, show the composition with a utility factor of zero and a utility factor of one for the NPCC (Northeast Power Coordinating Council) and MRO (Midwest Reliability Organization) grids. Those regions were chosen for comparison since they represent the lowest and highest electricity sector emission regions, respectively. ASCC = Alaska Systems Coordinating Council; FRCC = Florida Reliability Coordinating Council; HICC = Hawaiian Islands Coordinating Council; RFC = Reliability First Corporation; SERC = SERC Reliability Corporation; SPP = Southwest Power Pool; TRE = Texas Regional Entity; WECC = Western Electricity Coordinating Council; gCO_2eq/mile = grams of carbon dioxide equivalent per mile; GHG = greenhouse gas; PHEV = plug-in hybrid vehicle; UF= utility factor; ADR = assembly, disposal and recycling.

The percentage of the fuel cycle related emissions that result from gasoline consumption also varies significantly depending on the NERC region. The UF of 0.635 implies that 36.5% of the vehicle operation will be in charge sustaining mode. However, those regions that result in lower emissions with increased electric operation mode of the PHEV will have a higher share of the fuel cycle emissions coming from gasoline operation. The eight regions which have reduced emissions in electric mode, compared to gasoline mode, have the percentage of emissions related to the charge sustaining mode ranging from 36.9% to 50.3% of the total fuel cycle emissions. The two NERC regions which have higher emissions in electric mode operation, MRO and SPP, have 35.1% and 35.6% of their fuel cycle emissions coming from the charge sustaining mode.

1.3.4 Label Reflection of Energy

Total vehicle life cycle energy was also calculated using the life cycle model. Figure 10 contains a Sankey energy diagram, which shows the energy inputs, losses and final output to the vehicle. The figure reflects the energy flows for the Volt using a 0.635 utility factor. The electric fueling input energy is calculated using a national average for upstream, generation at the plant, and transportation and distribution losses. The figure shows that losses in the system account for over 44 percent of energy input. The largest losses in the system occur at the power plant during the generation of electricity from fuels. Upstream losses for gasoline extraction, production, transportation and distribution, also account for almost nine percent of input energy. The label value for energy consumption includes only losses due to charging, which is part of the EPA testing procedure for electrified vehicles.

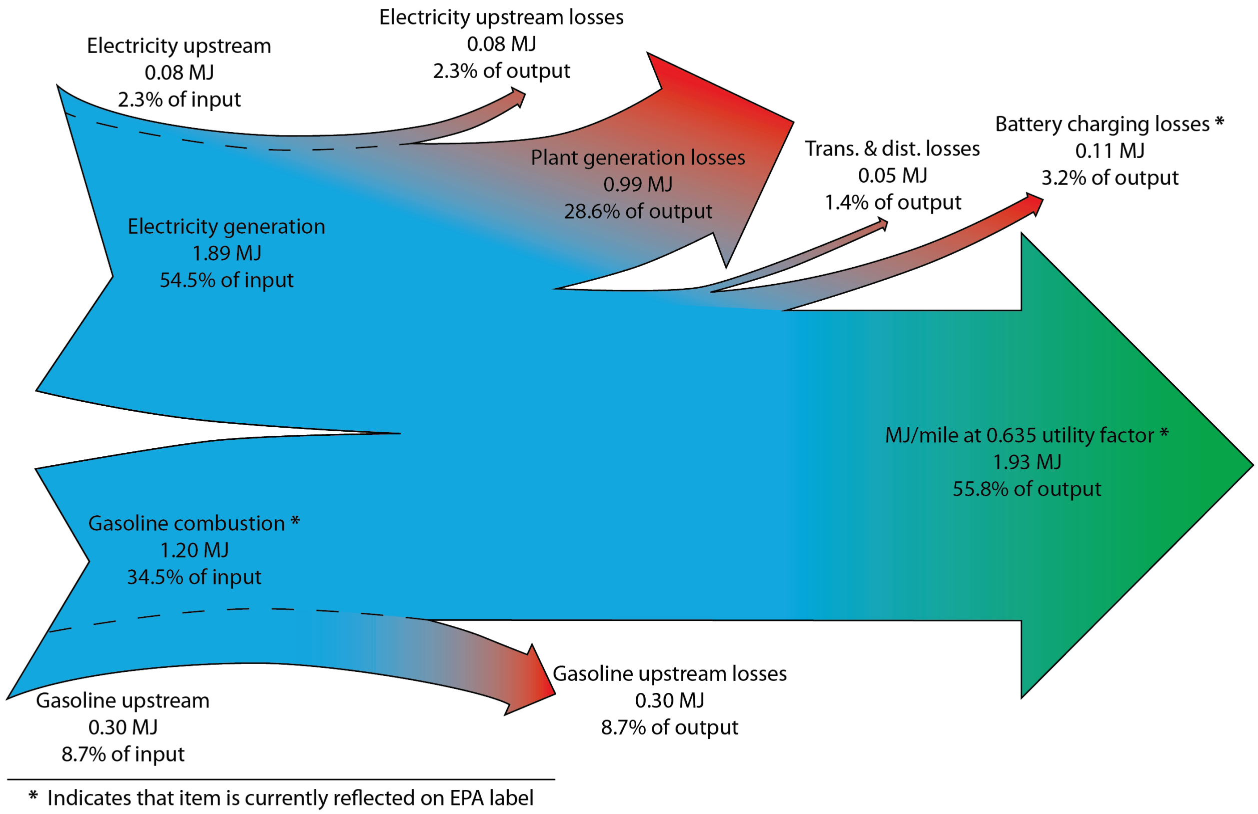


Figure 10 Energy flow diagram for Chevrolet Volt using a 0.635 utility factor and assuming national electrical grid averages. EPA = Environmental Protection Agency; Trans. = transmission; dist. = distribution; MJ = megajoule; MJ/mile = megajoules per mile.

1.3.5 Study Limitations

The electric emission data used in this study were all based on average emission factors. Other studies have shown that the GHG emissions for an electrified vehicle can vary widely dependent on factors such as time of day charging and charging source (Axsen et al. 2011; Kelly, MacDonald, and Keoleian 2012; Kintner-Meyer, Schneider, and Pratt 2007; Stephan and Sullivan 2008). For example, a vehicle charged at night could have a higher electric emissions rate than one charged during the day if the base load power for the region is dominated by carbon intensive fuel sources, such as coal. The fluctuation in electric fuels used to meet demand makes application of marginal emission factors difficult, hence the utilization of average factors for this study.

Data availability is another limitation to more comprehensive accounting of vehicle GHG emissions. For example, this research used the 2007 year data from the eGrid database to model electric sector combustion emissions. The 2007 year data was the latest data available. If regulatory agencies were to implement more specific regional standards however, more timely data would be needed to ensure that the standards and labeling efforts reflect the electric grid profiles.

The vehicle production and EOL emissions also suffer from lack of specific and timely emission data. The application of the GREET database to estimate the vehicle cycle emissions serves as a good tool for comparison between vehicle compositions and different vehicle technologies but lacks the ability to model more discrete differences between vehicles of the same type or class. A full vehicle specific life cycle assessment would be required to model vehicle production emissions at the accuracy needed for vehicle emission standards and labels.

1.4 Conclusion

The results from modeling the various eGrid regions of the U.S. show that there is far more life cycle emission variation over the total vehicle life cycle for PHEVs and EVs than for traditional gasoline only fuel vehicles. The results suggests that using only the fuel economy metric, or fuel consumption, to convey the relative GHG intensity of a vehicle will be insufficient for PHEVs and EVs. For example, only 25% of the GHG emissions from the Chevrolet Volt will be reflected on the 2012 EPA label. In contrast, 70% of the total life cycle GHG emissions of the conventional vehicle used for comparison, a 2011 Toyota Camry, will be reflected on the label and 63% for the 2011 Toyota Prius. Similarly, on an energy basis the EPA label will only reflect 59% of the total life cycle energy of the Volt since upstream factors for electricity and gasoline are omitted.

The variation in emissions between regions and states may make the use of a single national average GHG emission less complex and less confusing for consumers; however, by using a national average for upstream electric emissions, vehicles operating in regions with a low carbon grid are not fairly represented. Conversely, consumers in high carbon grid regions could choose an electrified vehicle, which would have higher life cycle GHG emissions than a comparative conventional vehicle in that region. The analysis shows that there is over 100 grams CO_2eq per mile difference between the lowest and highest GHG intensive NERC regions for PHEVs and over a 150 grams CO_2eq per mile difference for the full battery electric Nissan Leaf.

One recommendation for improvement to vehicle labeling, while recognizing the difficulty in reflecting GHG emissions accurately since these emissions are dependent on regional grid variability and driving patterns, is to include a range of emissions and highlight where different regions fall on the spectrum. With this addition, consumers would have access to a more detailed emission profile of a vehicle and will be able to make a more informed comparison of vehicles based on GHG emissions. Furthermore, the EPA should emphasize that a significant portion of GHG emissions from electrified vehicles are not captured by the label. Although the new label does direct consumers online to learn more about upstream emissions, stronger language on deficiencies of the label will help raise consumer awareness of the broader impacts of electrified vehicles. Emissions variability, due to regional electric grids, driving VMT differences, and vehicle production and EOL, highlight the need for increased GHG emission reporting for electrified vehicle labeling.

Chapter 2: Accounting for PEVs in GHG Standards

2.1 Introduction

Recent light-duty vehicle energy and greenhouse gas (GHG) emissions rulemaking by federal agencies has shown that governments are making a commitment to lower the fuel use and carbon footprint of their transportation sectors. The U.S. Environmental Protection Agency (EPA) finalized a ruling in August 2012 to regulate the GHG emissions from new light-duty vehicles produced by auto manufacturers in model years 2017-2025. The new standards require that these vehicles meet an estimated combined weighted average emissions level of 163 grams of CO_2 per mile (gCO_2/mi), which is equivalent to 54.5 miles per gallon (mpg) if the CO_2 requirements were met through only fuel economy (FE) improvements (U.S. Environmental Protection Agency and U.S. National Highway Traffic Safety Administration 2012b). This ruling comes just two years after new GHG rules for light-duty vehicles for model years 2012 through 2016, which required an emissions level of 250 gCO_2/mi, equivalent to 35.5 mpg if all efficiency improvements are made through increases in FE (U.S. Environmental Protection Agency and U.S. National Highway Traffic Safety Administration 2010). Vehicle electrification is seen as a promising technology that can partially help automakers meet their GHG targets, and can reduce the GHG intensity of the new vehicle fleet. The issue of how to account for plug-in electric vehicles (PEVs)[3] in GHG regulations is complex and controversial due to uncertainties and the various methods employed regarding allocation of emissions from electricity generation. Some of the uncertainties involved include the dynamic nature of the electricity grid (where the generation fuel mix can change drastically over the course of a day affecting the associated emissions profile of the PEV), changes in electricity generation sources over a period of years, and the fact that plug-in hybrid vehicles can utilize two very different fueling sources (liquid and electric). Of those uncertainties, the changes in the grid over time (evaluated per

[3] PEV is the term used in this thesis to refer to any vehicle which has electric grid connection ability (i.e.: plug-in hybrid vehicles and battery electric vehicles)

annum) and the difference in fueling for PEVs, are the two factors examined in this chapter.

Unlike conventional liquid fueled vehicles, the emissions profile from electrified vehicles can vary widely depending on the regional electricity fuel mix. Previous work has shown that PEV GHG emissions can vary widely depending on the carbon intensity of the grid (Stephan and Sullivan 2008; Elgowainy et al. 2010; MacPherson, Keoleian, and Kelly 2012; Ma et al. 2012; Hawkins et al. 2013; Anair and Mahmassani 2012). The regional variation in the carbon intensity of the electricity grid is important in determining how PEV emissions compare to conventional vehicles. For example, Samaras and Meisterling (2008) found that life cycle impacts from representative plug-in hybrid vehicles (PHEVs) were between 30% and 47% lower in a lower carbon intensive electric grid and between 9% and 18% higher on a high carbon intensive grid when the PHEV is compared with a comparable grid-independent hybrid electric vehicle (HEV).

Although the EPA does not project significant penetrations of PEVs out to 2025, projecting that PEVs will only account for 1% to 2% of total sales between 2017 and 2025, future stricter standards could incentivize automakers to produce substantially more PEVs (U.S. Environmental Protection Agency 2012e, 86; U.S. Environmental Protection Agency and U.S. National Highway Traffic Safety Administration 2012b, 62874). Greater penetration of PEVs into the light-duty vehicle fleet increases the importance of how to account for their fuel cycle GHG emissions.[4] Current U.S. EPA standards employ the use of projections of future PEV sales in order to determine the U.S. national electricity GHG emission factor (EF) applied to PEV electricity operation for compliance. However, because regional sales of PEVs, and the carbon intensity of regional electric grids, could be differ from the projections used in rulemaking, there exists a possibility that actual PEV emissions would differ from the projected average EF. This work will evaluate the use of a more comprehensive accounting methodology that

[4] Fuel-cycle refers to all energy and emissions that occur from cradle-to-tailpipe for conventional vehicles or cradle-to-vehicle for electric vehicles. Vehicles such as plug-in hybrids will have multiple fuel cycle pathways.

uses regional electricity EFs to calculate PEV emissions in regions where they are sold, instead of applying a projected EF. This study will assess if the use of a regional standard, and the added complexity involved in accounting for regional vehicle sales, is necessary in order to ensure that the emissions attributable to the charging of PEVs are being accurately accounted for in light-duty vehicle GHG regulations. This study further identifies the scale of omitted emissions if the EPA standard is applied to electric vehicles.

2.1.1 EPA Light-duty Vehicle GHG Standards Background

The issue of how to regulate GHG emissions for the light-duty PEVs sector is controversial due to the considerable complexity, and assumptions involved, in calculating the emissions for these vehicles. The EPA changed their approach in accounting for PEV GHG emissions between the 2012-2016 and 2017-2025 standards. In the former the EPA allowed PEVs to count as zero gCO_2/mi, for the electricity usage of these vehicles, up to a per manufacturer cumulative cap of 200,000 vehicles, for manufacturers that produce less than 25,000 PEVs and fuel cell vehicles (FCVs) in 2012, and 300,000 vehicles for manufacturers who produce over 25,000 in model year 2012. Above those caps, the net increase in upstream GHG emissions is calculated for PEVs. To calculate the associated GHG emissions from electricity, a nationwide full fuel cycle (cradle-to-wall outlet) average electricity GHG EF is used. However, since the standards only include the combustion emissions for conventional gasoline vehicles, the upstream GHG emissions attributable to a comparable ICEV of the same class as the PEV is subtracted from the electricity emissions of the PEV to account for this lack of upstream accounting for conventional ICEVs (U.S. Environmental Protection Agency and U.S. National Highway Traffic Safety Administration 2012b, 62822). EPA's rationale for initially providing the zero gCO_2/mi was to give automakers an incentive to build PEVs, which the EPA sees as a potential breakthrough technology that will help reduce GHG emissions from the light-duty vehicle fleet (U.S. Environmental Protection Agency and U.S. National Highway Traffic Safety Administration 2010, 25436–25437).

The 2017-2025 rule adds new complexity and incentives for PEVs. In the new ruling, PEVs and FCVs are given a zero gCO_2/mi with no limit on the number of vehicles that would be eligible for the credit through model year 2021 vehicles. In addition, the agency applies a multiplier to each PEV produced between 2017 and 2021. These multipliers are an additional incentive which allow automakers to count the zero compliance value up to two times for EVs and up to 1.6 times for PHEVs. There are no multipliers beyond 2021 and instead the zero compliance value is only allowed up to 600,000 PEVs, for manufacturers that sell 300,000 PEVs and FCVs between 2019-2021, and up to 200,000 for all other manufacturers (U.S. Environmental Protection Agency 2012f, 8).

Beyond the cap, for use of the zero emissions compliance value, the EPA has followed the precedence set by the 2012-2016 rule by accounting for the net upstream GHG emissions attributable to PEVs. This second round of standards employs a more complex approach to calculating the electricity GHG EF for use in determining the compliance value for PEVs. The updated approach utilizes the EPA's Integrated Planning Model (IPM) which employs a least-cost methodology to meet energy demand, environmental, transmission, dispatch, and emissions control constraints (U.S. Environmental Protection Agency 2010c). Their model splits the U.S. into 32 distinct electrical grid regions. The EPA relied on regional historical sales data for non-grid connected HEVs sold between 2006 and 2009 to find the amount of electricity used by PEVs. The past regional sales of these vehicles was used as a proxy for future PEV sales, which they forecast to represent approximately 3% of the new vehicle sales volume in 2025 (U.S. Environmental Protection Agency 2012e, 155). The agency then used the projected regional PEV sales to generate the electric demand in each region and used the IPM model to find the resultant grid fuel mix. In addition, the EPA developed a PEV charging profile from which they were able to estimate that 25% of PEV charging would be during the "on-peak" demand and 75% during "off-peak". Using these assumptions for regional sales, the amount of charging during peak electricity demand hours, and the IPM model least cost approach, the EPA found that the PEV electricity demand would constitute only 0.6% of

U.S. electric power consumption in 2030. In addition, they found that the projected electricity generation fuel mix attributable to PEV demand would be dominated by natural gas, making up 80% of the mix in 2030 (U.S. Environmental Protection Agency 2012e).

The final full fuel cycle electricity GHG EF published in EPA's final 2017-2025 ruling was 534 gCO_2/kWh (U.S. Environmental Protection Agency and U.S. National Highway Traffic Safety Administration 2012b, 62822). This is about 17% less than the 642 gCO_2/kWh national average electricity GHG EF applied in the 2012-2016 ruling (U.S. Environmental Protection Agency and U.S. National Highway Traffic Safety Administration 2010). The lower EF can be attributed to the higher percentage of natural gas generation in 2030 compared to that used for the 2012 rule, the distribution of PEV sales in areas with lower carbon intensive grid mixes, and the fact that, while the 2012 rule EF is based on a national average for the entire U.S. electricity sector, the 2017 rule EF is generated from the additional electricity demand from PEVs.

2.1.2 History of Accounting for PEVs in Standards

A wide range of different approaches for accounting for PEV emissions have been suggested in the literature and employed by policymakers, such as the EPA and the State of California's Air Resource Board (CARB) in their formal regulations (Lutsey and Sperling 2012; Andress, Dean Nguyen, and Das 2010; Creutzig et al. 2011). Each approach has features that appeal to different stakeholders. Some auto manufacturers, including Nissan, have advocated the use of the zero-compliance value for the electricity operation portion of PEVs arguing that automakers have no control over the fuel source for PEVs and that historically the government has only regulated emissions from the vehicle tailpipe (U.S. Environmental Protection Agency and U.S. National Highway Traffic Safety Administration 2012b, 62818). The EPA decided, however, that PEVs should be responsible for the net upstream GHG emissions, once the cumulative production cap for PEVs and FCVs is reached (U.S. Environmental Protection Agency and U.S. National Highway Traffic Safety Administration 2012b, 62811).

The approach used by EPA in their 2012-2016 standard utilized the U.S. average GHG emissions without consideration of regional PEV/FCV distribution. In the 2017-2025 standards EPA added complexity by using sales projections and grid projections to find a more specialized EF for application to all PEVs produced after the per-manufacturer vehicle cap is exceeded. The downside to this approach is that it does not incentivize automakers to sell vehicles in lower GHG regions and does not account for changes in regional sales distributions and electric grid fueling changes, which could occur between the final rule formulation and the actual regulatory year, when PEV compliance with GHG standards is assessed. Lutsey and Sperling point out that employing a policy with a regional lifecycle approach would create a framework which would be technology neutral and allow for a more standardized approach to alternatively fueled vehicles, including vehicles that run on natural gas or hydrogen (Lutsey and Sperling 2012, 314). The approach taken here is to evaluate if this regionalized methodology is necessary for future U.S. GHG standards for PEVs.

2.1.3 PEV Potential in Meeting Future Stricter GHG Standards

The 2012 and 2017 EPA light-duty vehicle GHG rules will effectively double the FE of the average vehicle in 2025, from a baseline year 1990. Figure 11 shows the historical and projected average GHG per mile emissions from the combined car and truck new light-duty vehicle fleet. The values from before 2012 are from the EPA's Fuel Economy Trends Report and represent the laboratory testing value, which is used in the vehicle GHG regulations and for Corporate Average Fuel Economy Standards (CAFE) (U.S. Environmental Protection Agency 2012b). The 2012-2016 and 2017-2025 standards are shown with the equivalent gasoline fuel economy in brackets next to the gCO_2/mi value.[5]

[5] Note that the conversion from the U.S. EPA light-duty vehicle GHG standard value to an equivalent mile per gallon of gasoline was done using a factor that one gallon of gasoline creates 8,887 grams of carbon dioxide when combusted (U.S. Environmental Protection Agency 2012b, 30). Other greenhouse gases are not included in the regulations but are instead capped at 0.01 gram per mile and 0.03 grams per mile for nitrous oxide (N_2O) and methane (CH_4) respectively. According to the EPA, if vehicles emitted at their cap for these other GHG emissions the N_2O and CH_4 emissions would represent between three to four additional grams per mile, on a CO_2 equivalent basis (U.S. Environmental Protection Agency and U.S. National Highway Traffic Safety Administration 2012b, 62799).

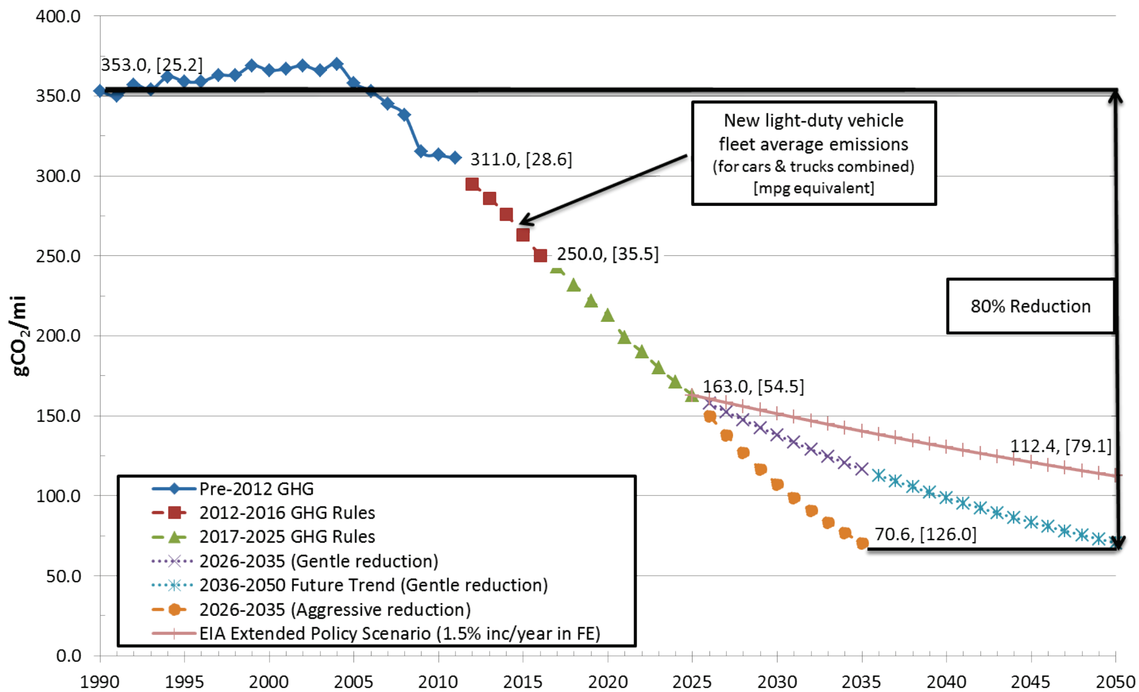


Figure 11 Past and future GHG standards and projections for the car and truck combined new light-duty vehicle fleet. The EIA reduction scenario is based on the Extended Policy scenario in the 2012 Annual Energy Outlook and is extrapolated out to 2050 past 2035, which is the final year of EIA forecasting. The gentle and aggressive reduction scenarios show the effect of an 80% reduction in GHG intensity from 1990 levels by 2035 (aggressive) and 2050 (gentle). Data sources: Lutsey (2012), EIA (2012b) and EPA (2012b)

Although the EPA has no proposed rules pending for model year vehicles produced beyond 2025, the 2012-2025 rules have set precedence upon which future standards can build to impose further reductions beyond the timeframe of the current standards. The State of California has indicated that they intend to target a reduction in their total GHG emissions of 80% below 1990 levels by 2050 (Governor of the State of California 2005). Lutsey found that this level of reduction in the vehicle market would be required by 2035 in order to account for a 15 year turnover of the vehicle fleet (2012, 187). This reduction, shown as the aggressive reduction line in figure 11, would effectively require the new light-duty fleet to meet a GHG target of 70.6 gCO_2/mi, which would be the gasoline FE equivalent of 126 mpg. These stringent standards would more than double the FE standard over a nine-year period, where the previous standards (spanning from

2012 through 2025) will almost double the average FE from the 2011 model year vehicles, over a span of 13 years.

There is a historical precedence for setting the national GHG standards for light-duty vehicles to follow the standards set by CARB. In 2004, CARB approved light-duty vehicle GHG standards, which would apply to new model year vehicles in years 2009-2016. These standards called for an overall reduction of 17% in climate change emissions from the vehicle fleet by 2020 and a 25% reduction by 2025 (State of California Air Resources Board 2012). In order to create harmony between the U.S. and the State of California regulations, the EPA worked with CARB to create standards that were comparable in stringency to the California's existing regulations. In 2009 California agreed to modify its regulations and accept the U.S. standards as equivalent compliance for auto manufacturers who sell vehicles in the state (U.S. Environmental Protection Agency and U.S. National Highway Traffic Safety Administration 2010, 25327–25328). The EPA worked closely with CARB on setting the stringency for the 2017 through 2025 standards in order to ensure that another harmonized single national standard would be achieved. It is reasonable to assume that the EPA may work together with CARB toward regulations concerning model year vehicles 2026 and beyond. Given that California is driven by the "80% reduction by 2050" target, future national GHG regulations set by the EPA for new light-duty vehicles may fall in line with this target.

The reliance on PEVs to meet these stringent targets is to be expected since the net upstream GHG emissions from electrified vehicles are much lower than conventional gasoline vehicles. For example, Lutsey and Sperling showed that the 2012 Nissan Leaf, with its unadjusted electricity consumption rating of 0.24 kWh/mi EPA GHG compliance value, would have an emissions rate of 104 gCO_2/mi, which is already significantly below the 163 gCO_2/mi EPA target for light-duty vehicles in 2025 (2012). Other studies have projected that PEVs will need to be a significant portion of the fleet if aggressive reductions in vehicle carbon intensity are to be realized (Melaina and Webster 2011; Leighty, Ogden, and Yang 2012; Williams et al. 2012). Increased penetrations of PEVs into the light-duty fleet will magnify the importance of accounting for their associated GHG emissions since they will be responsible for a larger portion of these emissions.

2.2 Methodology

The U.S. Energy Information Administration's (EIA) 2012 Annual Energy Outlook (AEO) was used to calculate projected vehicle characteristics, regional vehicle sales, and regional electric grid changes over time. The 2012 AEO projects changes in the transportation and electricity sectors, among others, through 2035. These projections were used as inputs for the model to observe which spatial and temporal parameters affected the electricity GHG EF attributable to PEVs for use in future EPA GHG regulations for light-duty vehicles.

2.2.1 Census Regions and Divisions

Projections for future new vehicle sales in the EIA AEO is divided regionally into different areas called "Census regions" and "Census divisions", shown in figure 12. The regions and divisions were established by the U.S. Census Bureau in 1910, with only the minor change of adding Alaska and Hawaii to the Pacific division in 1960 (US Census Bureau 2013). A regional analysis using these regions and divisions was chosen due to data availability and its established use for modeling by the EIA.

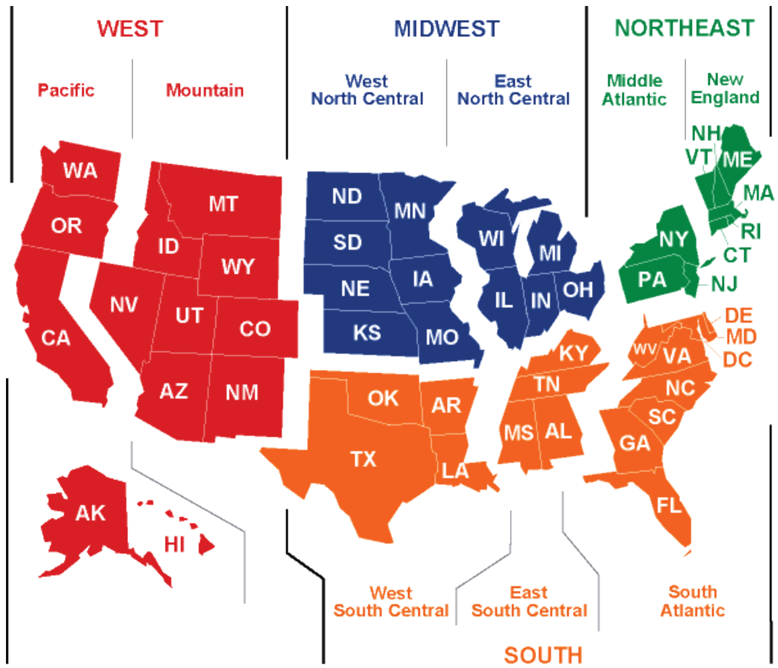


Figure 12 U.S. Census regions (Midwest, Northeast, South, and West) and divisions (East North Central, East South Central, Middle Atlantic, Mountain, Pacific, New England, South Atlantic, West North Central, and West South Central). Source: EIA (2009) AL = Alabama; AK = Alaska; AZ = Arizona; AR = Arkansas; CA = California; CO = Colorado; CT = Connecticut; DE = Delaware; DC = District of Columbia; FL = Florida; GA = Georgia; HI = Hawaii; ID = Idaho; IL = Illinois; IN = Indiana; IA = Iowa; KS = Kansas; KY = Kentucky; LA = Louisiana; ME = Maine; MD = Maryland; MA = Massachusetts; MI = Michigan; MN = Minnesota; MS = Mississippi; MO = Missouri; MT = Montana; NE = Nebraska; NV = Nevada; NH = New Hampshire; NJ = New Jersey; NM = New Mexico; NY = New York; NC = North Carolina; ND = North Dakota; OH = Ohio; OK = Oklahoma; OR = Oregon; PA = Pennsylvania; RI = Rhode Island; SC = South Carolina; SD = South Dakota; TN = Tennessee; TX = Texas; UT = Utah; VT = Vermont; VA = Virginia; WA = Washington; WV = West Virginia; WI = Wisconsin; WY = Wyoming

2.2.2 EIA AEO Scenarios Modeled

The 2012 EIA AEO includes 30 unique cases that modify the assumptions made in the Baseline (also referred to as reference) case. The EIA includes scenarios that vary the economic growth of the U.S., vary assumptions for costs and penetrations of energy technologies, allow for different government regulations, and allow for inclusion of market based climate change mechanisms. The scenarios in this study were chosen due to their potential to affect the transportation and electricity sectors, which are the sectors most relevant to the modeling efforts presented in this thesis and to PEV emissions regulations.

The EIA's Extended Policy (EP) scenario in the 2012 AEO assumes that all existing energy polices and legislation, except those requiring additional funding, are extended through the years modeled. This scenario also includes another round of light-duty vehicle FE standards which would require a fleet wide unadjusted (or CAFE rating) FE of 62 mpg by 2035 (U.S. Energy Information Administration 2012b, 220).

The Low Coal Cost (LCC) and Low Renewable Technology Cost (LRTC) scenarios provide an opportunity to look at scenarios that could increase the use of coal for electricity generation or increase renewable penetration, respectively, based on economic parameters. The LCC scenario increases regional productivity rates for coal mining and reduces costs for wages, mine equipment and transportation by 21 to 25%, relative to the reference case. The LRTC scenario assumes that costs for new nonhydropower based renewable technologies (i.e.: wind, solar, geothermal) are 20% lower in 2012 and reduce to 40% of the reference case value by 2035 (U.S. Energy Information Administration 2012b, 221).

A carbon fee scenario was also chosen to observe the affect that a large U.S. policy change could have on the electric grid and the transportation sector. The EIA's carbon fee scenario (GHG Tax) applies an economy wide fee of $25 per metric ton of CO_2 emissions in 2013 and increases the tax by 5% per year (U.S. Energy Information Administration 2012b, 222). Due to the yearly increase, the carbon fee applied in their model is $47 and $73 per metric ton in 2026 and 2035, respectively.

2.2.3 Electrical Grid Emission Factors

The EIA forecasts the composition of the electric grid generation for 22 supply regions. These supply regions correspond to the North American Electric Reliability Corporation (NERC) sub-regions, shown in figure 13 (U.S. Energy Information Administration 2012d). The 22 NERC sub-regions used for projecting future regional electricity generation are subsets of larger NERC regions, ten in total. The sub-regions are entirely composed of power control areas. The power control area is the entity which dispatches the power to the grid (Rothschild and Diem 2009).

Figure 13 Geographical representation of North American Reliability Corporation (NERC) sub-regions. Source: U.S. Environmental Protection Agency eGird Technical Support Document (2012c). AKGD = ASCC Alaska Grid; AKMS = ASCC Miscellaneous; AZNM = WECC Southwest; CAMX = WECC California; ERCT = ERCOT All; HIMS = HICC Miscellaneous; HIOA = HICC Oahu; MROE = MRO East; MROW = MRO West; NEWE = NPCC New England; NWPP = WECC Northwest; NYCW = NPCC NYC/Westchester; NYLI = NPCC Long Island; RFCE = RFC East; RFCM = RFC Michigan; RFCW = RFC West; RMPA = WECC Rockies; SPNO = SPP North; SPSO = SPP South; SRMV = SERC Mississippi Valley; SRMW = SERC Midwest; SRSO = SERC South; SRTV = SERC Tennessee Valley; SRVC = SERC Virginia/Carolina.

Since the EIA electricity grid modeling is based on NERC sub-regions a translation of these regions onto the Census regions and divisions is required. The percentage of electricity generation from each NERC sub-region within each Census region and division was calculated. This was done in order to represent the electrical grid of each Census region and division by using the NERC sub-region projections included in the AEO. The U.S. EPA's Emissions & Generation Resource Integrated Database (eGRID) was utilized to find this generation percentage for each NERC sub-region within each Census region and division. The 2012 edition of the eGRID database, which reports energy generation and emissions for power plants by state, NERC sub-region and NERC region in 2009, was used (U.S. Environmental Protection Agency 2012d).

The NERC sub-regions part of Alaska and Hawaii (Alaska Systems Coordinating Council's Alaska Grid and Miscellaneous; Hawaiian Islands Coordinating Council's Oahu and Miscellaneous) are not included in the EIA forecasting. The regions were assigned the

EFs from the eGRID database and no attempt was made to account for changes in these four grid regions over time. Both Alaska and Hawaii represent a relatively small percentage of the electricity generation, 1.8% and 2.9% respectively for the Pacific Census division, as calculated from the power plant generation data for 2009 in eGrid (see table B4 in appendix B for all NERC sub-region percentages within Census regions and divisions).

Each plant listed in the eGRID database is assigned a NERC sub-region and state code. In order to find the percentage of generation attributable to the Census region from each NERC sub-region, the electricity generation of any plant within the state's part of each Census region or division was summed. The generation attributable to each NERC sub-region was divided by the total generation for all of the plants in the Census region or division. The model assumes that the generation contribution percentage by each NERC sub-region, within each Census region and division, stays constant over time, since no projection related to this mapping methodology is provided in EIA's AEO.

$$e_n = \sum_{i=1}^{I} e_i \quad \forall\, i \in n \tag{7}$$

$$C_{nj} = \frac{\sum_{i=1}^{I} e_i}{e_n} \quad \forall\, i \in j \in z \in n \tag{8}$$

The calculation of the total generation percentage from all of the power plants within each Census region or division (*C*) is shown in equation 7. The generation from each plant (*i*), which is part of the NERC sub-region (*j*) and resides within the state (*z*), which is part of the Census region or division (*n*), is summed and then divided by the total generation in the Census region or division (e_n), in equation 8.

The total fuel cycle electricity GHG EFs for each NERC sub-region are calculated by multiplying the generation percentage (*l*) of each fuel type (*b*) by the upstream and generation EFs. The EFs used were from Argonne National Laboratory's GREET 1 2012 model. The upstream EF, in units of grams of CO_2eq emissions per kilowatt-hour (kWh) generated ($\dot{\boldsymbol{m}}_{\boldsymbol{1b}}$), includes the mining, extraction and transportation of the fuel to the electric generation plant. The generation factor ($\dot{\boldsymbol{m}}_{\boldsymbol{2b}}$), also in units of grams of CO_2eq emissions per kWh generated, only includes the emissions from the plant. (The electricity EFs by fuel type are contained in table B3 in appendix B)

$$\varepsilon_{ny} = \sum_{a=1}^{2}\left(\sum_{j=1}^{J} C_{nj}\left(\frac{\sum_{b=1}^{B} \dot{m}_{ab} * l_{jby}}{1-h_k}\right)\right) \;\forall\, a,b,j,k,n \qquad 9$$

The total EF (ε), the sum of upstream (a=1) and combustion (a=2), for each Census region or division is shown in equation 9. Using the EIA's generation by fuel type forecast for each fuel type in combination with the GREET EFs, and a "grid loss factor" (GLF) (h) allows for total fuel cycle electricity EFs of each NERC sub-region for each year (y) out to 2035. The GLF is needed to account for the transmission and distribution losses, which occur between the electric generating facility and the consumer. The eGRID database contains specific GLF's for the five different regions of the U.S. grid (k) (see table B1 in appendix B for specific GLF's used). These GLF's are applied to each NERC sub-region modeled.

2.2.4 Liquid Fueling Emission Factors

The upstream (well-to-pump) and combustion (tank-to-wheels) GHG EFs on a volumetric basis for gasoline, diesel, and ethanol fueled vehicles were derived from the GREET 2012 database (see table B6 in appendix B for the derivation of liquid fuel EFs). GREET EFs for different fuels can change based on varying assumptions on the fuel source and composition for each year up to 2020. The model used in this thesis includes changes in these fuel properties up to year 2020 and then assumes they stay constant out to 2035.

The combined upstream and combustion EF for vehicles running on gasoline was found using GREET's modeling of a low-level ethanol blend (10% ethanol). The gasoline portion of the low-level ethanol blend fuel is itself a blend of reformulated and conventional.

Flex-fueled vehicles can use either primarily gasoline or primarily ethanol fuel blends. The EF for when the vehicle is using a high ethanol level blend was found using GREET's modeling for a dedicated E85 (85% ethanol, 15% gasoline) vehicle. The EF for diesel is weighted between low-sulfur and conventional diesel fuel.

2.2.5 Vehicle Emissions Modeling

The total well-to-wheel emissions rate for each vehicle was calculated using the electricity and liquid fuel EFs calculated in the previous sections. Estimates for the new vehicle FE for 16 different vehicle types and 12 classes of vehicles (six for passenger cars and 6 for light-duty trucks) are included in the EIA AEO. Vehicles that use gasoline, diesel, ethanol, and electricity were the only types of vehicles included in this analysis. The EIA does include projections for other alternatively fueled vehicles, including vehicles that utilize natural gas, liquefied petroleum gases, and gasoline, methanol or hydrogen in a fuel cell. These vehicle classes were not considered in the analysis due to the complexity of including them in the model and since their combined sales only represented approximately 0.5% of cumulative new vehicle sales for the entire U.S. in all AEO scenarios considered in this analysis (U.S. Energy Information Administration 2012b).

The nine vehicle technology types evaluated were: gasoline, diesel, and ethanol flex fueled with internal combustion engines (ICE), battery electric vehicles with 100 and 200 mile ranges, plug-in hybrid electric vehicles with 10 and 40 all-electric ranges (AER) and both gasoline and diesel hybrid electric vehicles (HEV). The AEO includes FE projections for the 12 EPA vehicle classes (*c*) for each technology type (*x*) on a yearly basis (*y*). The six classes for cars are mini-compact, subcompact, midsize, large and two seaters. The six for light-duty trucks are small and large pick-ups, vans and utilities. If a technology is not projected to be available in a certain class then there is no FE projection published in the AEO for that particular vehicle.

$$r_{xcy} = \frac{1}{f_{xcy}} * g_{xy} \begin{cases} E10\ gasoline\ (G) if\ x = 1 \\ diesel\ (D)\ if\ x = 2 \end{cases} \tag{10}$$

The emissions on a per mile basis (*r*) can be calculated for gasoline and diesel fueled vehicles, including conventional and the grid independent HEVs, using equation 10, where the inverse of FE of the vehicle (*f*), in mpg, is multiplied by the liquid fuel EF (g_{xy}) where g_{1y} is for gasoline, for the year (*y*), and g_{2y} is for diesel.

$$r_{FFVcy} = \left(\frac{1}{f_{FFVcy}} * g_{1y} * \left(1 - p_y\right)\right) + \left(\frac{1}{f_{FFVcy}} * g_{3y} * p_y\right) \quad 11$$

For the ethanol flex fuel vehicle the EF (r_{FFV}) is the combination of the emissions from operating the vehicle on E10 and E85, as shown in equation 11. The variable *p* is introduced to represent the fraction of operation using E85 fuel. This fraction was derived from the AEO projection of E85 consumption for all light-duty vehicles and the total fuel consumption for ethanol flex fuel vehicles (see table B5 in appendix B for the derivation of this variable) (U.S. Energy Information Administration 2012b). It is assumed that the fraction of fueling using E85 in FFVs is the same for all vehicle classes modeled. There is also no adjustment in this model for the FFV FE between the FFV operating on E10 and E85. This limitation is due to there being no FE published specifically for FFV operating on either fuel but instead only a combined FE. It is important to note that if the FE numbers were separated that the FE for a FFV operating on E85 would be lower due to ethanol having a lower heating value than gasoline (Michael Wang 2012). The EF g_3 is introduced in equation 11 for the E85 fuel.

$$r_{EVcy} = \frac{1}{f_{EVcy}} * 33.705 * \varepsilon_{ny} \quad 12$$

Equation 12 is used to find the electric vehicle (EV) emission rate (r_{EV}). EVs in the AEO are assigned FE numbers in units of miles per gallon in gasoline equivalents (mpgge)

(f_{EV}). They are converted from mpgge in this model by using a conversion factor of 33.705 kWh per gallon of gasoline, which is the conversion factor used by the U.S. EPA to display energy information on new vehicle FE labels for PEVs (U.S. Environmental Protection Agency and U.S. Department of Transportation 2011, 39526). As shown in equation 12, the fuel consumption (FC), in kWh per mile, is multiplied by the EF, in grams of CO_2eq per kWh, for a Census region or division to find the full fuel cycle GHG emissions in grams CO_2eq per mile.

Plug-in hybrid vehicles are unique in that they can use a number of fuels in varying combinations. The EIA only publishes a combined FE number, which is a combination of the FEs for liquid fuel operation and electricity fuel operation. Without knowing the separate FE numbers for the PHEV during charge sustaining operation (gasoline engine enabled mode) or charge depleting operation (electric only mode) it is impossible to back calculate from the aggregated number published in the AEO. For simplicity of modeling, it is assumed that no gasoline is used during the charge-depleting mode and that during charge sustaining mode the PHEVs operate like a grid independent HEV (none of the stored electrical energy is used to power the vehicle during charge sustaining operation).

In absence of separate FE numbers for the two operation modes for the PHEVs, the approach used by Argonne National Laboratory in their VISION model was utilized in order to estimate these fuel economies. The VISION model uses the EIA AEO FE numbers for hybrid electric vehicles (HEV) to represent the gasoline consumption for a PHEV. There are two different all-electric range PHEVs that are modeled. PHEVs with a 10 (PHEV10) and 40 (PHEV40) mile all-electric range are included. Using a vehicle simulation software, Argonne found that the charge sustaining FE for a PHEV10 is 105% and a PHEV40 83% of the FE of a comparable HEV car. They found those factors to be 106% and 81% for light truck PHEV10s and PHEV40s respectively (Argonne National Laboratory 2012).

A utility factor (UF) is a measure of the fraction of miles driven in charge depleting mode compared to charge sustaining. For example, a UF of 0.6 implies that 60% of the miles traveled for that particular PHEV are in charge depleting mode. The UFs used for this model were from the Society of Automotive Engineers standard regarding PHEV UFs (2010). The multi day individual UF for the PHEV10 and PHEV 40 was found to be 0.271 and 0.667, respectively.

To find the FE for the charge sustaining mode of a PHEV the VISION model uses the combined FE for each PHEV published in the AEO and then back calculates the FE using the PHEV specific UF (*U*). The charge sustaining emission rate is found in this model by multiplying the FE of a HEV of the same class as the PHEV (f_{HEV}) by the correction factors from the VISION model (*v*). The FE is converted to fuel consumption (FC), in units of gallons per mile, and multiplied by both the gasoline EF, and by the fraction of driving in charge sustaining operation (equal to one minus the UF).

$$f_{PHEVEcy} = \left(\frac{1}{\frac{U}{\left(\frac{\frac{1}{f_{PHEVcy}} - (1-U)}{f_{HEVcy} * v} \right)}} \right) \begin{cases} PHEV10\ car:\ v = 1.05 \\ PHEV10\ truck: v = 1.06 \\ PHEV40\ car: v = 0.83 \\ PHEV40\ truck: v = 0.81 \end{cases} \quad (13)$$

$$r_{PHEVcy} = \left(\frac{1}{f_{HEVcy} * v} * l_{1y} * (1-U) \right) + \left(f_{PHEVEcy} * \varepsilon_{ny} * U \right) \begin{cases} PHEV10\ car:\ v = 1.05 \\ PHEV10\ truck: v = 1.06 \\ PHEV40\ car: v = 0.83 \\ PHEV40\ truck: v = 0.81 \end{cases} \quad (14)$$

Equation 13 is used to calculate the charge depleting (electric mode) FE (f_{PHEVE}) for the PHEV. To find the electric related emissions from the PHEV, one minus the UF is first subtracted from the FC of the PHEV (one divided by f_{PHEV}). This value is divided by the adjusted PHEV charge sustaining FE. The UF divided by this result is the calculated FE for the charge-depleting mode of the PHEV. The inverse of the FE is calculated to convert to FC for the next calculation step. The calculation of the PHEV emission rate (r_{PHEVy}) is shown in equation 14. First, the electric mode FC is multiplied by the Census region or division electricity EF. This charge depleting emission rate is added to the charge sustaining emission rate to find the total emission rate for the PHEV.

2.2.6 New Vehicle Fleet Modeling

New light-duty vehicle sales numbers are forecast in the AEO at the census division level for each vehicle type modeled (i.e.: diesel car, PHEV10 truck). A forecast for the percentage of each class (i.e.: mini-compact, large utility) is also published, but is aggregated to include all vehicle types (see table B7 in appendix B for the percentage by class). No specific class projection within each vehicle type is published. However, if the EIA does not forecast any sales of a certain class of vehicles, within a technology type, then a FE projection is not published. For example, no FE projection is made for large utility battery electric trucks with a 100-mile range (EV100) and sales of large car PHEV10's are not forecast until 2020 (U.S. Energy Information Administration 2012b).

$$\hat{S}_{xcy} = \frac{S_{xcy}}{\sum_{C=1}^{12} S_{xcy} \,\forall\, f_{xcy} \neq 0} \begin{cases} E10\ gasoline\ if\ x = 1 \\ diesel\ if\ x = 2 \\ Ethanol\ FFV\ if\ x = 3 \\ EV100\ if\ x = 4 \\ EV200\ if\ x = 5 \\ PHEV10\ if\ x = 6 \\ PHEV40\ if\ x = 7 \\ HEV\ diesel\ if\ x = 8 \\ HEV\ E10\ gasoline\ if\ x = 9 \end{cases} \qquad 15$$

Since the percentage of sales by class is not available for each vehicle type it is necessary to normalize the shares to find an approximation for the sales distribution for each year modeled, as shown in equation 15. For each type of vehicle (*x*), the sales shares (*S*) of each class (*c*) (from table B7 in appendix B) are summed when the FE forecast for that vehicle does not equal zero. The sales share is normalized so that the proportion for that vehicle type stays consistent. The normalized sales share for the class is represented by the variable $\hat{S}$.

Sales projections for each type of vehicle, at both the national and Census division level, are forecast in the AEO. The regional vehicle sales are based on a number of variables in the EIA AEO modeling including fuel prices, disposable income, number of licensed drivers, and driving demand (U.S. Energy Information Administration 2012c). Using these parameters the EIA is able to model what types of vehicles will be sold in different areas of the U.S. over time.

A sensitivity of these sales projections was included in the model to see what effect differences in regional sales could have on the weighted national average electricity EF. Differences of 10, 20, 50, 100 and 200% higher sales of PEVs in each Census area, at the region and division level, were evaluated. The variable λ is used to scale the sales, *q,* by the different sensitivity percentages. For instance, for a doubling of sales in a Census area (100% higher), λ is equal to two.

$$T_{ny} = \sum_{x=1}^{9} q_{wxy} * \lambda * \hat{S}_{xcy} * r_{xcy} * d_w \; \forall \; c \begin{cases} if\ c \leq 6; w = 1\ (car) \\ if\ c \geq 7; w = 2\ (truck) \end{cases} \qquad 16$$

The entire new vehicle fleet is modeled by utilizing the emission rate calculations and sales data. The total emissions (*T*) is calculated in equation 16. The life of the vehicle also must be considered when modeling the lifetime GHG emissions. The lifetime vehicle-miles traveled (VMT) used in the model comes from the GREET model for vehicle production which lists the lifetime VMT at 160,000 miles for passenger cars (d_1) and 180,000 miles for sport utility vehicles and pick-up trucks (d_2) (Michael Wang, Burnham, and Wu 2012). The subscript *w* in the equation is an index to distinguish between cars and trucks. The model assigns the emission rate for the vehicle in year *y* for the lifetime VMT of the vehicle. The reason the EF is held constant is that current EPA vehicle GHG emission standards are applied to the vehicle when it is produced and there is no attempt to include temporal fuel cycle emission changes, which may occur over the life of the vehicle, to EFs given at the year of production. Secondly, since no attempt is made to include the existing vehicle fleet in this model, it would be difficult to compare the changes in new vehicle fleet emissions if they are phasing in to the model over time.

2.2.7 Plug-in Electric Vehicle Energy Consumption

The amount of electricity consumed by each PEV needs to be calculated in order to find the weighted average regional electricity EFs.

$$E_{ny} = \sum_{x=4}^{7} \frac{1}{f_{xcy}} * U_x * \left(q_{wxy} * \lambda * \hat{S}_{xcy}\right) * d_w \; \forall \; c, w \begin{cases} EV100 \; if \; x = 4 \\ EV200 \; if \; x = 5 \\ PHEVE10 \; if \; x = 6 \\ PHEVE40 \; if \; x = 7 \\ w = 1 \; (car) \; if \; c \leq 6 \\ w = 2 \; (truck) \; if \; c \geq 7 \end{cases} \tag{17}$$

The total electricity consumption, in kWh, of all vehicles in the Census region or division (*E*) in year *y* is calculated in equation 17. The charge depleting FC of 100 and 200 mile range EVs, and 10 and 40 all-electric range PHEVs is multiplied by the utility factor[6], total sales of the vehicle type (multiplied by the normalized sales share for the vehicle class and sensitivity multiplier), and is multiplied by the lifetime VMT.

$$\mu_y = \sum_{n=1}^{N} \frac{E_{ny}}{\sum_{n=1}^{N} E_{ny}} * \varepsilon_{ny} \tag{18}$$

This fraction of the total electricity consumption, found in equation 17, of the national electricity consumption by PEVs, is then used to weight the national average electricity EF (μ), calculated in equation 18. The EFs calculated for each Census region and division in equation 9 are used for this weighting. The units for μ are in gCO_2eq/kWh.

2.2.8 Vehicle Production Calculation

In order to compare the different vehicle technologies included in the EIA AEO using a life cycle approach, the vehicle production was combined with the fuel cycle emissions calculated previously. The 2012 version of the GREET 2 model was used to estimate the vehicle production GHG emissions (Michael Wang, Burnham, and Wu 2012). Included in the model is a breakdown of different vehicle production processes, such as the manufacturing of components, the assembly, disassembly and recycling of the vehicle, battery production and fluids, such as motor and transmission oil. The GREET 2 model

[6] Note that the effective utility factor for the pure battery electric EV is equal to one since there is no secondary liquid fuel operation mode.

has the capability to simulate the production emissions burden of eight vehicle technology types including internal combustion engine vehicles (ICEV), HEV, PHEV's with 10, 20, 30 and 40 mile all-electric ranges, battery EV, and FCV. The model also includes distinct vehicle profiles for passenger cars, sport utility vehicles (SUVs), and pick-up trucks, meaning there are 24 different vehicle combinations available. The PHEV 20, PHEV 30 and FCV models were not included in this work.

A correlation exists between vehicle weights and the vehicle production emissions in the GREET 2 model. This correlation was found for each of the 15 vehicle technology types and class combinations (see figures B1, B2, B3 in appendix B). The vehicle weights were taken from the EIA AEO, which includes projected weights for conventional vehicles in 12 classes. The passenger car correlation was used for the six car classes, the SUV was used for the two van and two SUV classes, and the pick-up truck was used for the two pick-up classes.

One limitation of this method is that there is no adjustment for vehicle composition over time. One way that auto manufacturers could design vehicles to meet more stringent GHG emission requirements is to use lightweighting techniques, which commonly employ the use of materials such as aluminum, magnesium and carbon fiber. These materials have different life cycle emissions properties, depending on sourcing and how they are used to lightweight vehicles, which could change the production related life cycle emissions (Michael Wang, Burnham, and Wu 2012; McMillan and Keoleian 2009; Sullivan, Burnham, and Wang 2010; Schmidt et al. 2004; Ungureanu, Das, and Jawahir 2007; Geyer 2008; Lewis, Kelly, and Keoleian 2012).

Table 1 Scaling factors for the vehicle weights compared to the ICEV (Internal combustion engine vehicle) Dervied from: GREET 2 (Michael Wang, Burnham, and Wu 2012)

	ICEV	HEV	PHEV10	PHEV40	EV
Passenger Car	1.00	1.08	1.09	1.29	1.43
Sport Utility Vehicle	1.00	1.09	1.11	1.32	1.52
Pick-Up Truck	1.00	1.09	1.11	1.32	1.56

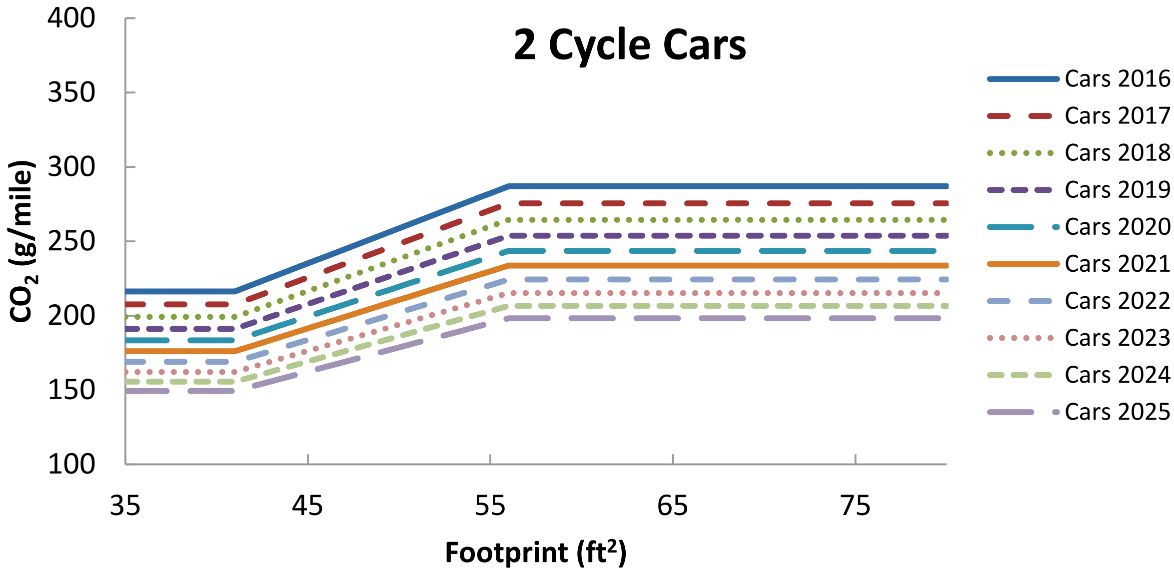
Since the vehicle weights in the AEO are projected only for conventional cars a scaling factor was required in order to model other technologies. The GREET default weight for the ICEV for each of the three main classes (passenger car, sport utility and pick-up) was used as the baseline to determine the scaling factors for the other technologies (i.e. HEV, EV). The defaults listed in the GREET model for each technology were divided by the baseline ICEV weight for that class to find the scaling factors, shown in table 1. As an example, if the weight listed in the AEO for an ICEV small sport utility in year *y* was 4,000 lbs., the EV small sport utility in the same year would be modeled with a weight of 6,080 lbs. The scaling factors, like the vehicle composition, are not altered over the years modeled. The average new conventional vehicle passenger car and light truck weight decreased by 478 lbs. and 556 lbs. respectively, between 2012 and 2035 in the AEO EP scenario.

$$V_{wxy} = \left(\alpha_{wx}\left(W_y * \widehat{W}_{wx}\right) + \beta_{wx}\right) * d_w \tag{19}$$

The vehicle production related emissions (*V*) were calculated using equation 19. The weight of the ICEV (*W*) in year *y* was multiplied by the scaling factor ($\widehat{W}$) to find the adjusted weight. This adjusted weight was multiplied by the slope of the GREET weight correlation (α) and the intercept of this correlation (β) was added. Since the GREET correlation factors are on a per mile basis, the production emissions were multiplied by the lifetime miles traveled (*d*).

2.2.9 Extrapolation of the EPA GHG Curves

The physical size of the PEVs that will be produced by automakers is important since the EPA light-duty vehicle GHG emission regulations are based on the footprint of the vehicle. For a number of reasons the EPA and National Highway Traffic Safety Administration (NHTSA) decided on a footprint based standard instead of an average for all vehicles. The agencies believe that an attribute standard is preferred since it would encourage automakers to implement fuel efficiency improving technologies across their fleet since the compliance is derived from their new vehicle fleet mix. Other reasons included not incentivizing automakers to make smaller vehicles which could make them less safe, helping to spread the burden of compliance more evenly across auto manufactures, and ensuring consumer choice is not disrupted by allowing auto manufacturers to continue producing similarly sized vehicles to the ones preferred by consumers prior to the rulemaking (U.S. Environmental Protection Agency and U.S. National Highway Traffic Safety Administration 2012a, 2–1,2–2). The footprint of the vehicle, for use in the standard, is defined as the average of the front and rear track widths multiplied by the vehicle wheelbase (U.S. National Highway Traffic Safety Administration 2010) (U.S. Environmental Protection Agency and U.S. National Highway Traffic Safety Administration 2010, 25330).



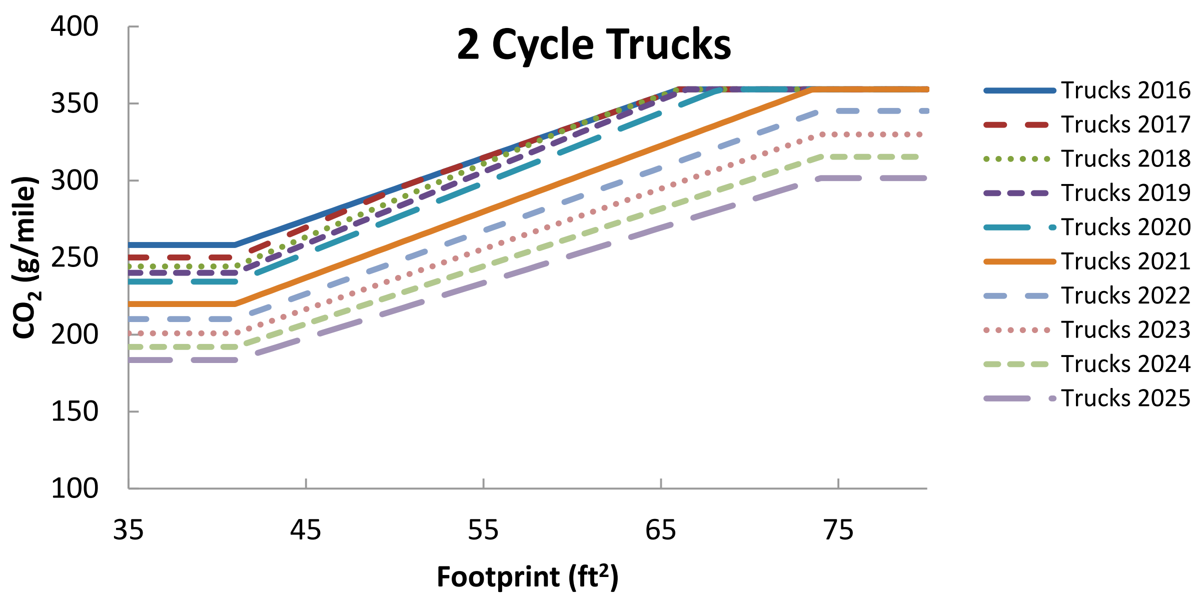


Figure 14 EPA GHG target footprint curves for cars and trucks for the 2017 through 2025 rule. The 2016 curve is shown for reference. Source: U.S. EPA (2012a)

The curve fitting model used by the EPA for their 2017 through 2025 ruling was utilized to extrapolate the car and truck GHG footprint based curves (U.S. Environmental Protection Agency 2012a). There are two sets of curves generated in the EPA model. The first called ‘EPA curves’ represents the total gCO_2/mi target by vehicle footprint. The second called ‘2 cycle curves’ represent the stringency assuming a certain amount of air conditioning (A/C) credits will be applied to the vehicles each year. Effectively this means that the 2 cycle curves represent the CO_2 emission target from the combination of the city and highway FE tests and therefore represent a less stringent version than the ‘EPA curves’, since they assume a certain amount of CO_2 reduction will come from A/C improvements.

In order to extrapolate the curves for model year vehicles in 2026 and beyond a number of assumptions used by the agency in their curve-fitting model were used or adjusted. The agency used a sales-weighted approach to developing the curves for the final 2017 and later GHG regulations (U.S. Environmental Protection Agency and U.S. National Highway Traffic Safety Administration 2012b, 62696). Since the data they used to develop their forecasts of sales for each vehicle model is only published out to year 2025, an assumption was made, in the extrapolation, that the sales of each model for years 2026 through 2035 would be equal to the sales forecast by EPA for model year 2025 light-duty vehicles.

The amount of A/C credits used by auto manufacturers to meet the EPA standards also varies in the agency’s curve fitting model. In the initial year (2017), the agency assumes that 12.8 and 12.0 gCO_2/mi will be applied toward meeting the GHG targets for cars and trucks, respectively. For years 2021 and on, the agency assumes that the maximum amount of A/C credits allowed will be used by auto manufacturers toward meeting the standard, equal to 18.8 and 24.0 gCO_2/mi for cars and trucks, respectively (U.S. Environmental Protection Agency and U.S. National Highway Traffic Safety Administration 2012a, 5–59). The maximum allowed use of A/C credits is assumed constant in the extrapolation made out to 2035.

The stringency applied to the extrapolation of model year 2026 through 2035 new vehicles is 8.02% per year. This is the average stringency required to reduce the new vehicle fleet from the EPA target of 163 gCO_2/mi for cars and trucks combined, down to 70.6 gCO_2/mi to meet the GHG goals established by California and the timeframe discussed by Lutsey (2012, 187). This stringency is more than double the CO_2 emissions reduction of 3.5% per year for years 2017 through 2021 and 60% higher than the 5% per year average annual rate of reduction for years 2022 through 2025 in the EPA regulations (2012f, 4).

2.3 Results and Discussion

The importance of accuracy in accounting for PEV emissions in vehicle standards will depend on two main factors. First, how strongly these vehicles infiltrate the new vehicle fleet will be a factor in deciding how comprehensive and to what level of specificity the emissions accounting needs to be for PEVs. One reason for this is that the zero gCO_2/mi emission credit and the credit multipliers included in the EPA standards are primarily a way to incentivize auto manufacturers to produce PEVs. If PEV sales are weak, but the agency continues to value PEVs as a "game changing" GHG reduction technology, then it is probable that EPA would continue the zero credit in standards for model year 2026 vehicles and beyond. Furthermore, if sales are low then it may not be in EPA's best interest to employ complicated electricity related GHG emission accounting methodologies. The GHG emissions accounting methodology for FCVs, for example, is not explicitly included in the 2017-2025 EPA rules, but EPA does state that FCVs would be accounted for using the net upstream approach used for PHEVs and EVs, beyond the production cap (U.S. Environmental Protection Agency and U.S. National Highway Traffic Safety Administration 2012b, 62811). Effectively the EPA is acknowledging that FCVs will be responsible for upstream GHG emissions, but they have not finalized a specific accounting method due to the expected low sales of these vehicles and hence are not expected to have any significant penetration into the new vehicle fleet or an effect on the GHG reduction targets of the regulations (U.S. Environmental Protection Agency and U.S. National Highway Traffic Safety Administration 2012a, 3–2, 3–3).

The second main factor influencing whether EPA should employ regional accounting, is how different the GHG emissions from PEVs are between the current methodology, which uses projected future sales in different regions and applies this weighted EF to vehicles produced, and the methodology being evaluated in this article, which applies regional EFs to actual vehicle sales. If there is little difference between the current EPA methods and the regional sales weighted EF for PEVs then it would not be in the best interest of the EPA to add the complexity of tracking vehicle sales to the buyer and applying regional EFs.

2.3.1 Future New Vehicle Fleet Emissions

The GHG emissions from the projected new vehicle fleet are shown in figure 15 for the baseline and EP scenarios. The leftmost bar associated with each year represents the life cycle emissions of vehicles produced in each model year over their lifetime. The stacked rightmost bar for each year represents the liquid and electric full fuel cycle emissions over the lifetime of the vehicles produced in each model year. It is important to note that the peak of new vehicle fleet emissions in year 2015, which shows up in both graphs, is primarily driven by steady projected increases in new vehicle sales, which start at 9.8 million in 2009 and rise to 17.6 million in 2035 for the Baseline case and 17.0 million in the EP case. The new vehicle sales were much stronger in the first half of the 2000's with average total sales of cars and truck. According to Ward's Auto, U.S. new vehicle sales averaged 17.3 million units for years 2000 through 2004 inclusive, while sales decreased to an average of 15.0 million units for years 2005 through 2009 inclusive (2013). The lowest sales came in 2009 with only 10.6 million (Johnson and Kanal 2013). 2009 represented the lowest sales of new vehicles since 1982. The EIA forecast of 17.6 million new vehicle sales in 2035 is just below the highest sales ever recorded of 17.8 million in 2001 (Ward's Auto 2013).

The steepest ascent of sales, in the EIA forecast, is between the years 2009 and 2016 where vehicle sales increase by an average of 740,000 new vehicles per model year. The relative flatness of emissions in the baseline case is driven by an assumption of low FE improvements over the time period forecasted, where the average new vehicle starts at 29 mpg in 2009 and only rises to 38 mpg in 2035. Conversely, the vehicle efficiency improvements incorporated into the EP scenario raise the FE projection to 62mpg in 2035.

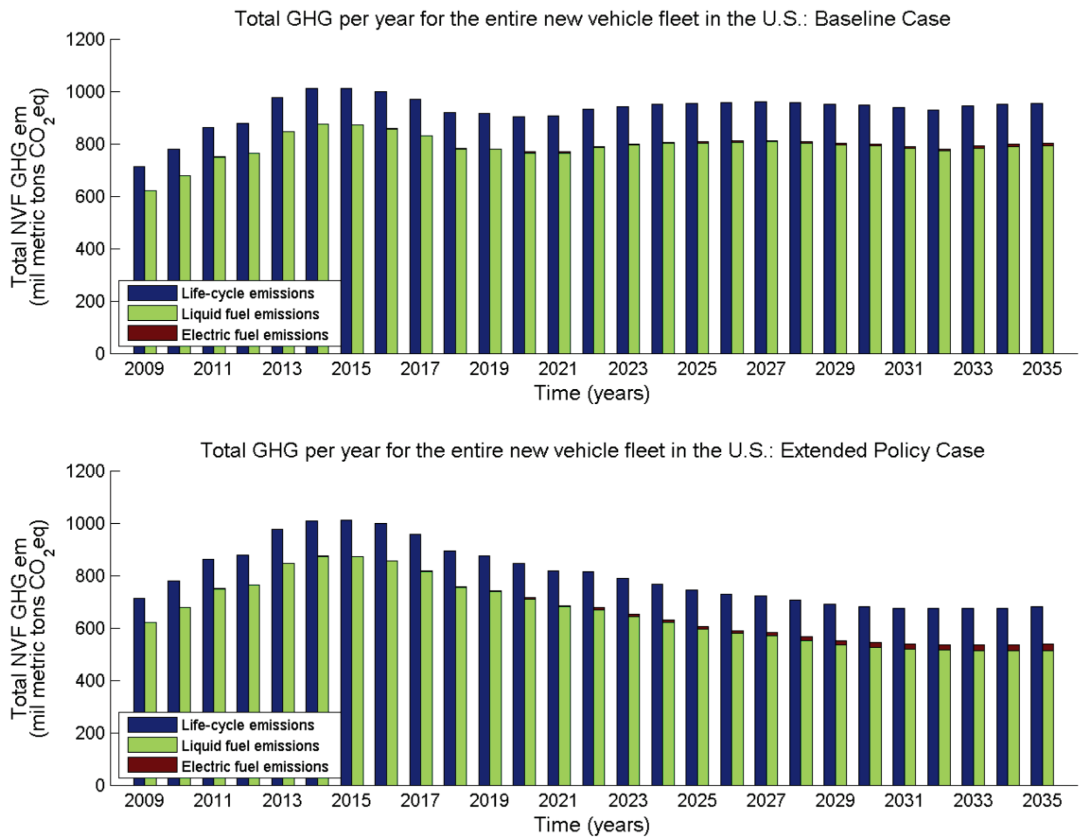


Figure 15 GHG emissions from the projected new vehicle fleet showing the life cycle, emissions from liquid fuels and from electric fuels using a U.S. national emission factor specific to each year modeled. NVF = New vehicle fleet

The percentage of GHG emissions attributable to PEVs (in electric operation) is also drastically different between the two scenarios. In the baseline case, PEV electric emissions only account for 0.7% of total fuel cycle emissions in 2026 and 1.3% in 2035, while in the EP case they account for 2.0% and 4.6% for each year respectively. This low impact from PEVs on the total fuel cycle emissions of the new vehicle fleet is primarily due to their low penetration of 4.3% and 9.7% of new vehicle sales in 2026 and 2035, in the EP case. However, cumulatively projected PEV sales in the EP case reach 11.8 million between the years 2026 and 2035. In fact, in this scenario, PEV sales in the years 2022 through 2025 are projected to reach a cumulative 2.2 million, which is above the 600,000 per manufacture cap for use of the zero gCO_2/mi credit. Although the emissions attributable to PEVs are projected to be low, as a percentage of the new vehicle fleet fuel cycle emissions, the actual projected sales show that emissions accounting for the electric operation of these vehicles will become relevant once manufacturers produce over the 2022-2025 PEV compliance credit caps.

The new vehicle fleet lifetime emissions, broken down by vehicle technology type, are shown in figure 16. The figure shows that although PEVs increase their share of emissions, over the 26-year period modeled, the overall new vehicle fleet emissions are still dominated by conventional gasoline and TDI (turbo direct injection) diesel vehicles, flex fueled vehicles, and grid-independent HEVs. These vehicle technologies account for 68.9%, 15.8%, and 7.6% respectively, of the life cycle GHG emissions for the 2035 model year new light-duty vehicle fleet. Combined, this means that only 7.8% of the life cycle emissions of the 2035 new vehicle fleet lifetime are attributable to PEVs. The reason that the PEVs account for a higher percentage of the life cycle new vehicle fleet emissions than they do for the fuel cycle is due to the vehicle production related emissions reflected in the life cycle value. In addition to the increased weight of PEVs compared to conventional vehicles (refer to table 1), the emissions per pound are also slightly higher for the electrified vehicles. For instance, a 3,000 lb. total weight conventional gasoline passenger car, PHEV40, and EV100 modeled in GREET have emission rates of 47.9, 50.5, 49.5 gCO_2eq/mi, respectively (assuming the same vehicle lifetime miles traveled for the three vehicle types) (Michael Wang, Burnham, and Wu 2012).

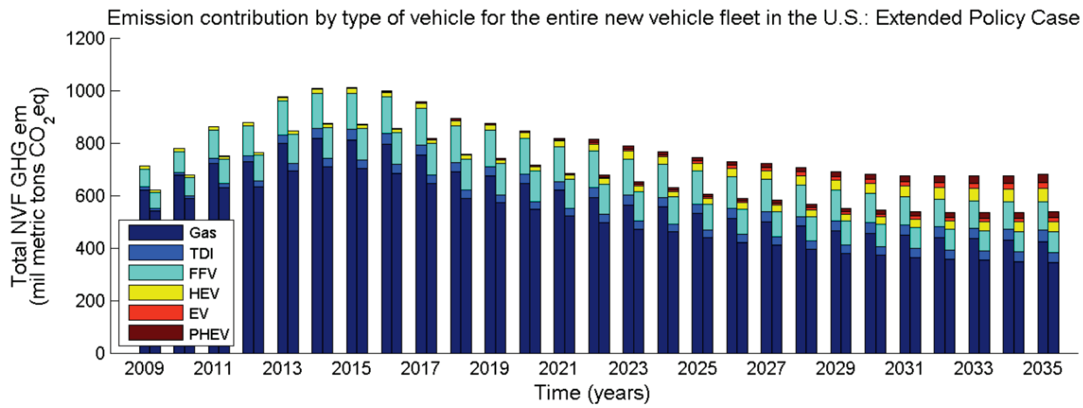


Figure 16 Emission contibution filtered by vehicle type. Life cycle emissions shown by bar on left for each year and full fuel cycle shown as right bar EV = Electric vehicle; FFV = Flex fuel vehicle HEV = Hybrid electric vehicle; NVF = New vehicle fleet; PHEV = Plug-in electric vehicle; TDI = Turbo direct injection (diesel vehicle)

The data presented in figure 15 and figure 16 used the projected average electricity EF for the entire U.S. Figure 17 shows all of the different technologies that went into the new vehicle fleet model and presents the breakdown of the life cycle component emissions for all vehicle types, within the passenger car sector, and for the Census divisions with the lowest and highest carbon intensity electricity grids. The life cycle emissions value is shown on a per mile basis, using the lifetime miles traveled for passenger cars, on top of each stacked bar. The top graph shows the results using the EIA AEO data for the year 2012, while the bottom two graphs are for the 2035 model year forecasts. The baseline case is indicated in the top two graphs while the bottom graph shows the results for the EP case. The EP case will have the same results as the baseline in 2012, so only the baseline case results are shown for that initial year.

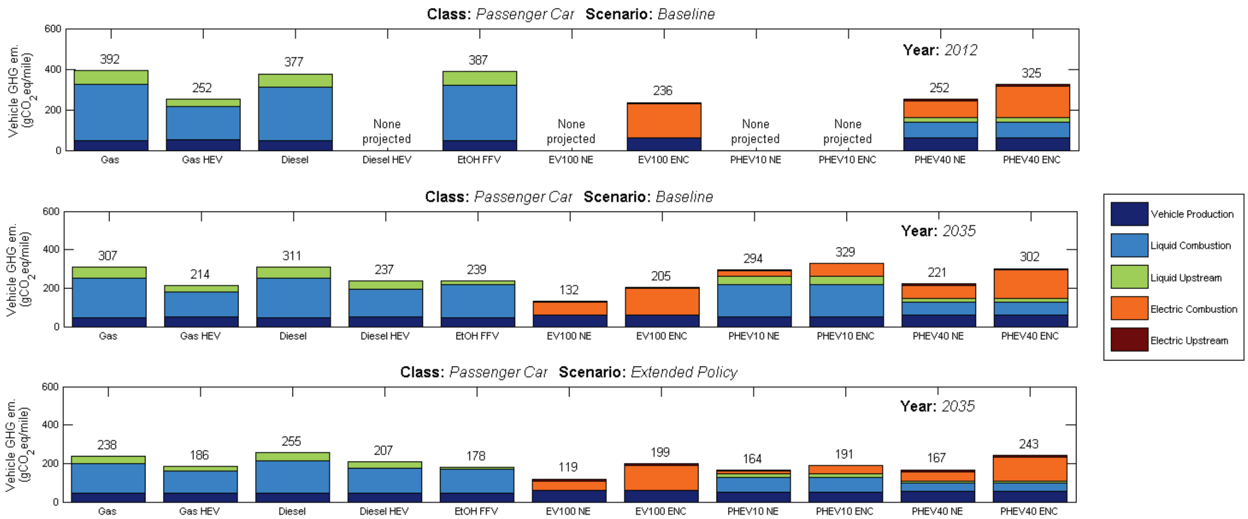


Figure 17 Life cycle GHG emission components for each vehicle type ENC = East North Central; NE = New England; EtOH FFV = Ethanol Flex fuel vehicle; EV = Electric vehicle; HEV = Hybrid electric vehicle; PHEV = Plug-in electric vehicle, Em. = Emissions

The figure demonstrates that it is difficult to choose one vehicle technology type that has universally the lowest or highest life cycle emissions profile. All vehicle types drastically improve over the 23-year period in the EP scenario; however, the percentage difference between types is less in 2035 than the reference year. The gasoline HEV is 36% lower than the conventional gasoline vehicle in 2012 but only 22% lower in 2035. The PHEV40 operated in the Census division with the highest carbon intensity electricity grid, the ENC (East North Central) division, shows a reduction of 17% below the conventional gasoline vehicle in 2012, but an increase of 2% in 2035.

Among the three PEV types shown in figure 17, the EV with a 100-mile range is the only vehicle that shows a substantial difference when compared to the other vehicles in the same region. Operating in the lowest carbon intensive electricity Census division, NE (New England), the EV100 has a 27% lower life cycle value than the PHEV10 and 29% lower than the PHEV40, in the EP case. The comparison between types in the ENC region does not show a technology that results in a substantial reduction in life cycle emissions. The EV100 is actually 4% higher than the PHEV10, in the ENC Census division.

In this high carbon region the non-grid connected gasoline HEV is lower, albeit only slightly, by 3% compared to the PHEV10 and 6.5% compared to the EV100.

This comparison exemplifies the difficulty in determining which technology will result in the most GHG reductions per distance traveled. The regional differences for the PEVs are significant in determining if a PEV is more or less GHG intensive than conventionally fueled vehicles. The PHEV40 is shown to be worse than the gasoline HEV, diesel HEV and ethanol FFV, using a blend of gasoline and ethanol, in the ENC division, but this same vehicle has a lower emission intensity than all of those vehicles when operated in the NE division, in the EP scenario.

2.3.2 EV Compliance Using Regional EFs Compared to Footprint Curves

Once the per-auto manufacturer zero-emissions compliance sales cap for PEVs is exceeded, automakers will need to consider how PEV compliance will fit within the EPA footprint based standard. Figure 18 shows the actual 2025 and the extrapolated 2035 EPA footprint GHG curve for passenger cars. The extrapolated curve is based on the new vehicle fleet meeting a 70.6 gCO_2/mi GHG standard. The GHG emissions in gCO_2eq/mi for each EV100 vehicle class in year 2035 is plotted with a marker indicating the emission rate for the vehicle operating in each Census division and an 'X' representing the U.S. average.[7] The emissions compliance rates for each vehicle class are plotted on the x-axis at the median footprint value of the EPA class ranges. The footprints for the classes modeled using EIA forecasts are defined in the EPA and NHTSA's Joint Technical Assessment (2012a, 1–32)(see in table B8 in appendix B). The size of the marker for each Census division is representative of the relative sales in the division compared to the total sales of EV100s in the U.S. It is clear from the figure that although the NE Census division has the lowest compliance value, it is also the smallest region in terms of sales

[7] Note that the plotted emissions include CH_4 and N_2O emissions while the EPA curves do not. These greenhouse gases were included in all other parts of the modeling effort and the convention to include them is continued here for consistency. Without these gases included, the emission rates shown in figure 18 would be slightly lower. EPA states that if conventional vehicles were to emit at their tailpipe cap for CH_4 and N_2O these vehicles would emit three to four grams per mile on a CO_2 equivalent basis (U.S. Environmental Protection Agency and U.S. National Highway Traffic Safety Administration 2012b, 62799). For reference, the GHG per generation of electricity is about 7% higher than the CO_2 only emission factor for the U.S. average mix projected for 2012 (Michael Wang 2012).

and only accounts for 4% of projected EV100 sales in 2035 in the EP scenario. The South Atlantic (SA) division compliance value is very close to the U.S. average and it is projected to account for the highest percentage of EV100 sales at 24% of total in 2035.

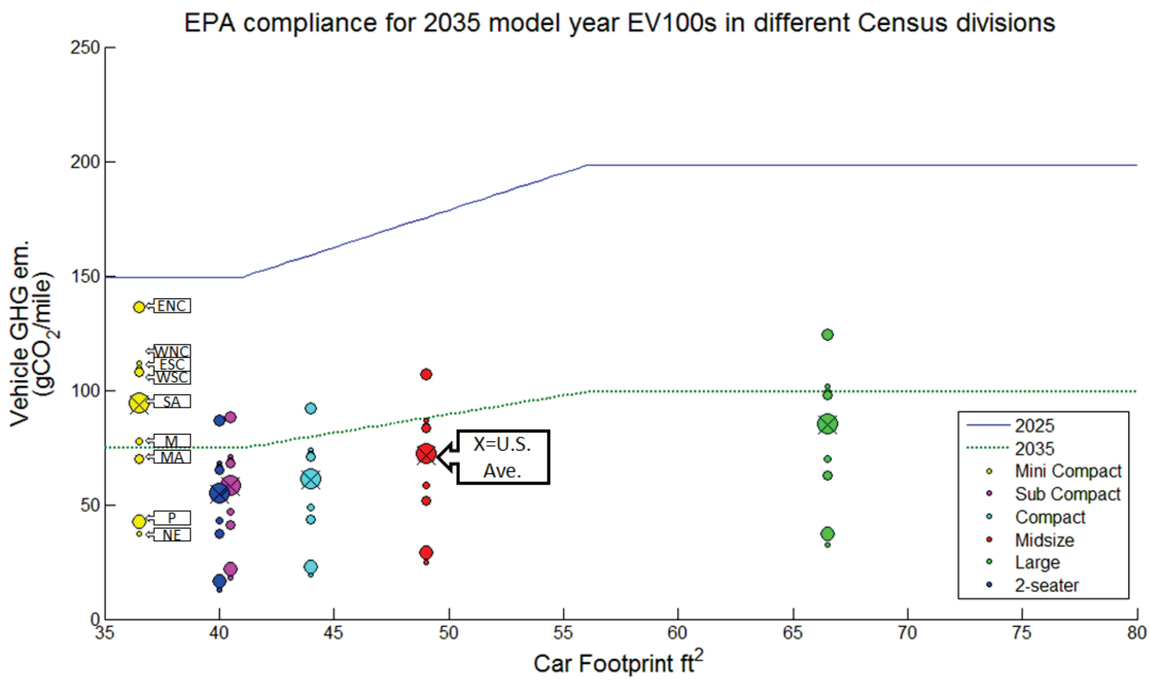


Figure 18 EPA passenger car CO_2 emissions footprint based curve for 2025 and extrapolated curve for 2035. Each EIA vehicle class is plotted for each Census division using 2035 EIA forecast data (Note: Vehicle class markers are in gCO_2eq, curves are in gCO_2 [see footnote 7]). ENC = East North Central; ESC = East South Central; MA = Middle Atlatic; M= Mountain; NE = New England; P = Pacific; SA = South Atlantic; WNC = West North Central; WSC = West South Central

As discussed in the introduction, an important caveat of the PEV compliance values are that the EPA adjusts the total fuel cycle emission rates by subtracting the associated upstream emission burden from a conventional gasoline vehicle of the same footprint, since the regulations for conventional vehicles do not include accounting of upstream GHG emissions. Since the EIA modeling does not produce a forecast based on meeting the 70.6 gCO_2/mi target discussed in this chapter, a slightly different approach was used than the one utilized by the EPA. For this model, the upstream of the equivalent vehicle class conventional gasoline vehicle forecast in the AEO was subtracted from the calculated EV100 full fuel cycle emissions rate (in gCO_2eq/mi) to reflect the effective compliance rate for the EV in each Census division.

Except for the mini-compact class, the EV100 would meet or exceed its footprint based target using the U.S. average electricity EF in seven out of the nine Census divisions in 2035 when assuming a median footprint area within each class. The mini-compact class is unique in the AEO forecasts because it is the least fuel-efficient despite having the smallest size.[8] This analysis demonstrates that the majority of electrified vehicles would meet an aggressive 2035 standard, which accounts for the regional EFs, and these vehicles could play a major role in helping auto manufacturers meet their GHG compliance targets.

2.3.3 PEV Compliance: Regional Electricity EF Sensitivity Analysis

The wide range of compliance values shown in figure 18 demonstrates that if a regional accounting approach was to be used for these vehicles that not all vehicles in all regions would meet the 2035 extrapolated footprint-based target modeled. The difference in compliance values for these EV100s between the highest and lowest compliance Census divisions ranges from 70 gCO_2eq/mi for the subcompact class to almost 100 gCO_2eq/mi for the mini-compact class.

The overall sales weighted EF may not reflect this large variation if the regional distribution of PEVs, and their electricity usage, follows the regional electricity generation. Figure 19 shows the difference between the full fuel cycle electricity EF used by the EPA in their 2017-2025 regulations, the projected U.S. average EF, and the effective EF by weighting the electricity usage of PEVs in Census regions and divisions and using EFs and projected PEV sales specific to the Census areas, in both the years

[8] In the 2035 EP scenario the EIA projects mini-compact EV100s will have an average FE value of 162 mpgge while the subcompact class, the next larger class, is projected to have an average FE of 229 mpgge. One possible rationale for this discrepancy is that the sales of mini-compact EV100s are not projected until 2027 while sales for the subcompact class start in 2009. The assumption here may be that because manufacturers do not begin to produce mini-compacts until 18 years after subcompacts that the mini-compacts will not be optimized, and hence are not as efficient on a size basis, relative to the other vehicle classes.

2026 and 2035. The EPA EF is shown for reference but, as noted in the introduction (and in footnote 7), the agency's methodology includes a different set of assumptions and parameters compared to the ones used in this paper.

Both the Census regions and divisions were evaluated to see what effect a more aggregated (Census region) weighted EF would look like compared to the more disaggregated (Census division). Included on the Census regional and divisional bars are sales sensitivity bars that show how different the weighted EF would be if there were higher sales in either the region (or division) with the highest EF (high bar) or the lowest EF (low bar). This analysis was done for the five different EIA scenarios most applicable to the transportation and energy sectors.

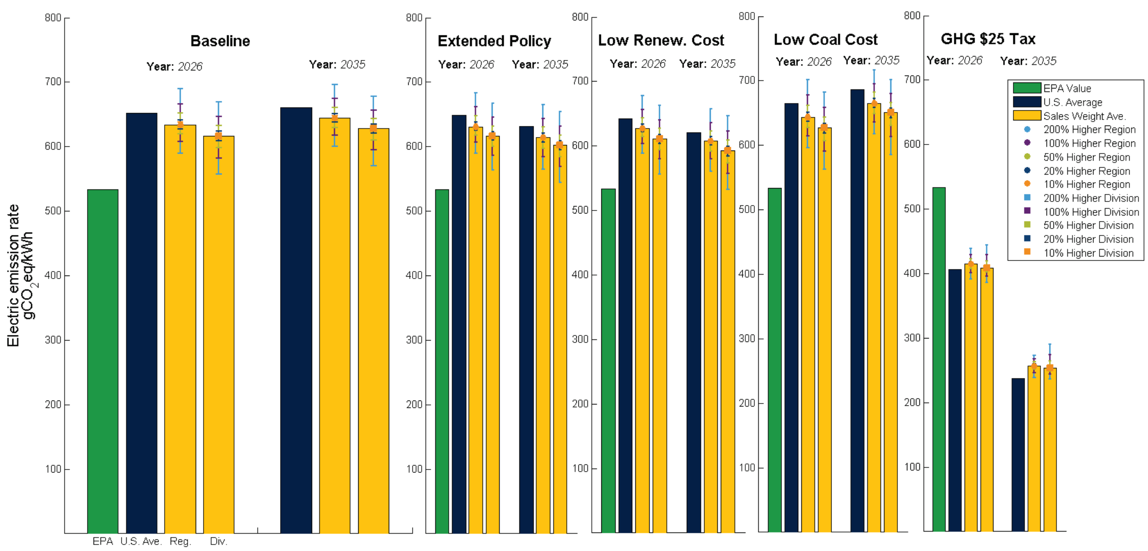


Figure 19 Average electricity emission factor shown for different calculating methodologies, scenarios and years. U.S. Ave. = United States Average; Reg. = Region; Div. = Division; Renew. = Renewable

The results in the figure show that there is not a significant difference between using regional (or divisional) factors and using a U.S. average to represent the combined EF. In the 2035 baseline scenario the difference between the weighted Census regional and divisional EFs and the U.S. average is only 15.6 and 31.4 gCO_2eq/kWh respectively. The divisional weighted EF is 4.8% lower than the projected U.S. average EF. This same trend holds where the divisional EF is between 4.5% and 5.7% lower than the U.S. average for the two years in the baseline, EP, LRTC, and LCC scenarios. The aggressive carbon tax scenario (GHG $25) is the only scenario where the regional and divisional EFs are higher than the U.S. average EF (less than 2% higher for both aggregation types in 2026, 7% and 8% higher for the divisional and regional in 2035).

The difference in higher sales in any one region also represented a relatively small difference from the initial sales allocation projected by the EIA. A doubling of sales in the Census division, relative to the initial allocation, with the lowest and highest electricity carbon intensity changed the sales weighted average EF by -5.5% and +4.9%, respectively, in the 2035 EP scenario. A tripling increased the difference to -9.6% and +8.7% than the weighted EF with the original sales allocation. This same trend held for Census regions and for both years modeled in the baseline, EP, LRTC and LCC scenarios. The carbon tax scenario showed similar results, except for the Census division weighting in 2035, which showed that a tripling of sales would mean the weighted EF could be as much as 6.9% lower or 14.4% higher. The difference in terms of gCO_2eq/kWh was smaller from the other scenarios. For instance, the Census division EF that was 14.4% higher due to a tripling of sales in the most carbon intensive division (in year 2035), was a quantitative difference of 36.6 gCO_2eq/kWh This difference, in the carbon tax scenario, is a full 15.7 gCO_2eq/kWh lower than the high EF found for a tripling of sales, in the most carbon intensive division, in the 2035 EP scenario.

The results show that there are only modest differences between the EF using the initial sales allocation and the EF assuming the highest or lowest carbon intensive areas have increased sales. The other finding was that the EFs in the EP, LRTC, and LCC scenarios were not dramatically different when compared to the baseline scenarios. The only scenario that showed a large deviation was the carbon tax scenario, where the U.S. average EF was almost three times lower than the baseline in 2035.

2.3.4 Study Limitations

There are a number of limitations to the method used here to evaluate regional standards for PEVs. First, the modeling in this paper relied on forecasts that are largely static for many of the input parameters. One example of this is the small change in the percentage of generation by different electricity fuel sources forecast in the 2012 AEO. The baseline scenario assumes that 21% of the electricity generation in the U.S. will come from natural gas in 2013, increasing to 24% in 2035.[9] A similar static outlook is made for renewables, which begin at 13% in 2013 and increased to 14% in 2035. There are slightly larger variations for the EP, LRTC and LCC scenarios but the EFs only change by a maximum of 6% compared to the baseline case. The carbon tax scenario does induce large changes into the grid, where coal reduces to less than 1% of generation in 2035, however, this case would require a dramatic change in energy policy for the U.S.

Another limitation of this analysis is the level of aggregation used to evaluate the regional EF policy for PEVs. Census regions and divisions were used since those were the smallest areas for which EIA issues forecasts. However, there is no precedent set for an agency such as the EPA to institute Census level area policies. If a regional standard were ever to be utilized by an agency, an evaluation of the best level of aggregation would be necessary. Employing a regional policy that uses the Pacific Census division as one defined area would be difficult to justify, given that the states of Alaska and Hawaii are included. These two states have very different electricity generation profiles than the states included from the contiguous U.S. In 2009, Hawaii and Alaska generated over 75% and 17%, respectively, of their electricity from oil. For comparison, only 2% of the electricity produced in the States of California, Oregon and Washington, the other states in the Pacific Census division, was from oil (U.S. Environmental Protection Agency 2012d).

[9] The effect of the increased use of fracking to provide cheap natural gas remains to be seen, but if trends continue then there is a high probability that the EIA's 2012 AEO baseline case would underestimate the amount of generation from natural gas. Electricity generation from natural gas does surpass coal in EIA's most aggressive 'carbon tax' scenario by 2020, however, and natural gas has already begun to close gap and accounted for just over 30% of the net electricity generation in the U.S. in 2012, which is an increase of 5.6% over 2011 (U.S. Energy Information Administration 2012a). Further, the EIA's Electric Power Monthly report shows the percentage of electricity generation from coal dipping below 38% in 2012, which is the same generation percentage for coal projected for 2035 in the 2012 version of the EIA's AEO (U.S. Energy Information Administration 2012b; U.S. Energy Information Administration 2012a).

Other issues could arise if the political and technical challenges of a regional policy were overcome and this accounting methodology was instated at the state or state cluster level. If the regional regulation made selling PEVs in one state attractive to automakers, in order to lower the vehicle's compliance value, but a bordering state was assigned a high EF, then consumers in the high compliance value state could decide to cross over state lines to purchase the vehicle. This scenario would allow for errors in the accounting of PEV related emissions since the EF applied would be from a state with a low carbon intensive EF but the vehicles would be charged on a grid with a high EF. Furthermore, a regional standard could be seen as reducing consumer choice since automakers would be less likely to sell vehicles in areas with a high compliance value. This is important since, as discussed in the introduction section, the EPA chose an attribute based footprint standard partially to protect consumer choice.

2.4 Conclusions and Future Work

In the absence of a huge policy shift, such as implementing an economy wide carbon tax, the small changes in the EFs derived from the EIA forecasts suggest that the complexity involved in tracking and accounting for regional (or divisional) PEV sales will not dramatically increase the effectiveness of the regulations to capture PEV electricity related emissions. If a large policy shift, such as a carbon tax, were to occur then a reevaluation of the EF applied to PEVs should be conducted to reflect the changes in the electricity grid. Even with a large policy change, such as a carbon tax, the regional variation was shown to be small, and a tripling of sales in any one Census division changed the weighted emissions factor by less than 15%.

Although the results from evaluating a regional GHG emissions compliance accounting methodology for PEVs would not be beneficial, given modest electricity grid projections and regional sales forecasts, there is still a need for policy to keep from incentivizing PEVs in regions with high carbon intensity electric grids. In such regions the electrified vehicles could have higher GHG emissions operating on electricity compared to gasoline, as demonstrated by figure 8 in chapter 1, or may have higher emissions when compared to a grid-independent HEV. Future work will focus on alternative policies and incentives used by agencies, such as the EPA, in their current standards, and other policy makers. The aim of this analysis would be to find policies that aim to maximize the GHG reduction potentials of PEV deployment.

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Appendices

Appendix A

Table A1 Total vehicle life cycle CO_2eq emissions for each North American Reliability Corporation (NERC) region, NERC sub-region and state for the Volt at a 0.635 utility factor. gCO_2eq/mile = grams of carbon dioxide equivalent per mile; ASCC = Alaska Systems Coordinating Council; FRCC = Florida Reliability Coordinating Council; HICC = Hawaiian Islands Coordinating Council; MRO = Midwest Reliability Organization; NPCC = Northeast Power Coordinating Council; RFC = Reliability First Corporation; SERC = SERC Reliability Corporation; SPP = Southwest Power Pool; TRE = Texas Regional Entity; WECC = Western Electricity Coordinating Council; AKGD = ASCC Alaska Grid; AKMS = ASCC Miscellaneous; AZNM = WECC Southwest; CAMX = WECC California; ERCT = ERCOT All; HIMS = HICC Miscellaneous; HIOA = HICC Oahu; MROE = MRO East; MROW = MRO West; NEWE = NPCC New England; NWPP = WECC Northwest; NYCW = NPCC NYC/Westchester; NYLI = NPCC Long Island; RFCE = RFC East; RFCM = RFC Michigan; RFCW = RFC West; RMPA = WECC Rockies; SPNO = SPP North; SPSO = SPP South; SRMV = SERC Mississippi Valley; SRMW = SERC Midwest; SRSO = SERC South; SRTV = SERC Tennessee Valley; SRVC = SERC Virginia/Carolina; AL = Alabama; AK = Alaska; AZ = Arizona; AR = Arkansas; CA = California; CO = Colorado; CT = Connecticut; DE = Delaware; DC = District of Columbia; FL = Florida; GA = Georgia; HI = Hawaii; ID = Idaho; IL = Illinois; IN = Indiana; IA = Iowa; KS = Kansas; KY = Kentucky; LA = Louisiana; ME = Maine; MD = Maryland; MA = Massachusetts; MI = Michigan; MN = Minnesota; MS = Mississippi; MO = Missouri; MT = Montana; NE = Nebraska; NV = Nevada; NH = New Hampshire; NJ = New Jersey; NM = New Mexico; NY = New York; NC = North Carolina; ND = North Dakota; OH = Ohio; OK = Oklahoma; OR = Oregon; PA = Pennsylvania; RI = Rhode Island; SC = South Carolina; SD = South Dakota; TN = Tennessee; TX = Texas; UT = Utah; VT = Vermont; VA = Virginia; WA = Washington; WV = West Virginia; WI = Wisconsin; WY = Wyoming; gCO_2eq/mile = grams of carbon dioxide equivalent per mile.

NERC Region	ASCC		WECC																											
gCO_2eq/mile	307		291																											
NERC Sub-Region	AKGD	AKMS	AZNM							CAMX	NWPP												RMPA							
gCO_2eq/mile	324	240	321							258	275												394							
State	AK	AK	AZ	CA	CO	NV	NM	OK	TX	CA	AZ	CA	CO	ID	MT	NV	NM	ND	OR	UT	WA	WY	AZ	CO	MT	NE	NM	SD	UT	WY
gCO_2eq/mile	307	307	313	245	383	313	381	351	331	245	313	245	383	193	359	313	381	435	225	397	207	430	313	383	359	342	381	319	397	430

NERC Region	TRE				FRCC	HICC		MRO												
gCO_2eq/mile	325				321	361		376												
NERC Sub-Region	ERCT				FRCC	HIMS	HIOA	MROE			MROW									
gCO_2eq/mile	325				321	339	369	373			376									
State	LA	NM	OK	TX	FL	HI	HI	IL	MI	WI	IL	IA	MI	MN	MT	NE	ND	SD	WI	WY
gCO_2eq/mile	306	381	351	331	325	361	361	306	341	361	306	383	341	353	359	342	435	319	361	430

NERC Region	NPCC											
gCO_2eq/mile	272											
NERC Sub-Region	NEWE							NYCW	NYLI	NYUP		
gCO_2eq/mile	277							263	353	257		
State	CT	ME	MA	NH	NY	RI	VT	NY	NY	NJ	NY	PA
gCO_2eq/mile	261	242	320	257	313	288	180	313	313	260	313	317

NERC Region	RFC																					
gCO_2eq/mile	342																					
NERC Sub-Region	RFCE							RFCM			RFCW											
gCO_2eq/mile	301							368			356											
State	DE	DC	MD	NJ	NY	PA	VA	IN	MI	OH	IL	IN	IA	KY	MD	MI	OH	PA	TN	VA	WV	WI
gCO_2eq/mile	387	525	332	260	313	317	310	413	341	385	306	413	383	418	332	341	385	317	334	310	403	361

NERC Region	SPP												
gCO_2eq/mile	372												
NERC Sub-Region	SPNO					SPSO							
gCO_2eq/mile	385					366							
State	AR	CO	KS	MO	OK	AR	CO	KS	LA	MO	NM	OK	TX
gCO_2eq/mile	317	383	376	383	351	317	383	376	306	383	381	351	331

NERC Region	SERC																																			
gCO_2eq/mile	335																																			
NERC Sub-Region	SRMV							SRMW					SRSO						SRTV												SRVC					
gCO_2eq/mile	296							382					350						355												307					
State	AR	LA	MS	MO	OK	TN	TX	IL	IN	IA	KS	MO	AL	FL	GA	LA	MS	SC	AL	AR	GA	IL	IN	KY	MS	MO	NC	TN	VA	WV	GA	NC	SC	TN	VA	WV
gCO_2eq/mile	317	306	322	383	351	334	331	306	413	383	376	383	331	325	340	306	322	283	331	317	340	306	413	418	322	383	320	334	310	403	340	320	283	334	310	403

Table A2 eGrid grid loss (transportation & distribution) factors for five U.S. regions and total U.S. average (U.S. Environmental Protection Agency (2011a)).

Region	Gross Grid Loss Factor (%)
Alaska	1.24
Eastern Grid	6.47
Hawaii	3.20
Texas	6.42
Western Grid	4.84
U.S. Average	***6.16***

Table A3 Final upstream electric emission factors and associated data used to derive them. These factors are listed either as grams of emissions per Btu input, or as grams of emissions per kWh generated at the plant.

	Natural Gas				
Emission Type	*CO_2*	*CH_4*	*N_2O*	*CO_2eq*	*Units*
Plant input heat rate*	0.298				m^3/kWh
Upstream emission rate*	48.0	0.437	1.0E-4	60.0	g/kWh
Upstream emission rate /Heat rate	160.9	1.47	3.35E-4	197.7	g/m^3
Energy content of fuel+	36,593				Btu/m^3
Final upstream emission rate^	**4.4E-3**	**4.0E-5**	**9.16E-9**	**5.4E-3**	g/Btu

	Bituminous Coal				
Emission Type	*CO_2*	*CH_4*	*N_2O*	*CO_2eq*	*Units*
Plant input heat rate*	0.442				kg/kWh
Upstream emission rate*	30.0	4.1E-3	4.14E-4	30.2	g/kWh
Upstream emission rate /Heat rate	67.9	9.28E-3	9.37E-4	68.4	g/kg
Energy content of fuel+	21,535				Btu/kg
Final upstream emission rate^	**3.15E-3**	**4.31E-7**	**4.35E-8**	**3.18E-3**	g/Btu

Lignite Coal					
Emission Type	*CO_2*	*CH_4*	*N_2O*	*CO_2eq*	*Units*
Plant input heat rate*			0.782		kg/kWh
Upstream emission rate*	70.0	0.888	2.35E-4	92.3	g/kWh
Upstream emission rate /Heat rate	89.5	1.14	3.0E-4	118.0	g/kg
Energy content of fuel+			21,535		Btu/kg
Final upstream emission rate^	**4.16E-3**	**5.27E-5**	**1.4E-8**	**5.48E-3**	g/Btu

Residual Fuel Oil (RFO)					
Emission Type	*CO_2*	*CH_4*	*N_2O*	*CO_2eq*	*Units*
Plant input heat rate*			0.263		liter/kWh
Upstream emission rate*	98.0	0.043	6.8E-4	99.3	g/kWh
Upstream emission rate /Heat rate	372.6	0.162	2.59E-3	377.4	g/liter
Energy content of fuel+			39,544		Btu/liter
Final upstream emission rate^	**9.42E-3**	**4.09E-6**	**6.54E-8**	**9.55E-3**	g/Btu

Distillate Fuel Oil (DFO)					
Emission Type	*CO_2*	*CH_4*	*N_2O*	*CO_2eq*	*Units*
Plant input heat rate*			0.333		liter/kWh
Upstream emission rate*	111.0	0.049	7.9E-4	112.5	g/kWh
Upstream emission rate /Heat rate	333.7	0.148	2.38E-3	338.1	g/liter
Energy content of fuel+			36,642		Btu/liter
Final upstream emission rate^	**9.11E-3**	**4.05E-6**	**6.48E-8**	**9.23E-3**	g/Btu

	Biomass				
Emission Type	*CO_2*	*CH_4*	*N_2O*	*CO_2eq*	*Units*
Final upstream emission rate[#]	**2.4**	**1.51E-4**	**6.0E-5**	**2.42**	g/kWh

	Nuclear				
Emission Type	*CO_2*	*CH_4*	*N_2O*	*CO_2eq*	*Units*
Final upstream emission rate[#]	**10.8**	**2.25E-3**	**5.61E-5**	**10.9**	g/kWh

[*] Input heat rate and emission rate are from the USLCI database (National Renewable Energy Laboratory 2008) accessed from SimaPro software.
[+] The source for the energy content of fuel was from the Annual Energy Review Appendix A (U.S. Department of Energy 2010)
[^] This is equal to the 'upstream emission rate' divided by the 'heat rate' divided by the 'energy content of the fuel'.
[#] For biomass and nuclear fuel types the USLCI database (National Renewable Energy Laboratory 2008) only provides the final emissions in terms of grams per kWh, not input heat rate (in units of Btu) at the plant level
Note: kWh = kilowatt-hour; g = gram; kg = kilogram; m = meter; Btu = British thermal unit; CO_2 = carbon dioxide; CH_4 = methane; N_2O = nitrous oxide; CO_2eq = carbon dioxide equivalent.

Table A4 Gasoline emission factors in grams of emission per gallon of fuel.

Source	Phase	*CO_2*	*CH_4*	*N_2O*	*CO_2eq*
GREET Low-Level Ethanol Gasoline Values[i]	Upstream	1,574	11.80	0.33	**1,968**
	Combustion	8,810	0.34	0.28	**8,902**
U.S. EPA Gasoline Values[ii]	Upstream	-[iii]	-	-	-
	Combustion	8,887[iv]	-	-	-[v]

Note: GREET = Greenhouse gases, Regulated Emissions, and Energy use in Transportation; EPA = Environmental Protection Agency; CO_2 = carbon dioxide; CH_4 = methane; N_2O = nitrous oxide; CO_2eq = carbon dioxide equivalent.

[i] These values are from the GREET Version 1.8d database (M. Wang 2010).
[ii] U.S. EPA emission value for gasoline is shown for comparison to the GREET values used in the article.
[iii] The U.S. EPA estimates that the combustion CO_2 emissions from gasoline should be multiplied by a factor of 1.25 to account for the upstream CO_2 emissions (2011e).
[iv] Source value: U.S. Environmental Protection Agency (2011e).
[v] The U.S. EPA reports that CO_2 accounts for 95-99% of the GHG emissions from a vehicle but no specific CO_2eq number is given (2012b).

Appendix B

Table B1 eGrid grid loss (transportation & distribution) factors for five U.S. regions and total U.S. average for 2009 electric grid areas (U.S. Environmental Protection Agency 2012d)

Region	Gross Grid Loss Factor (%)
Alaska	5.84
Eastern Grid	5.82
Hawaii	7.81
ERCOT (Texas)	7.99
Western Grid	8.21
U.S. Average	***6.50***

Table B2 Fuel properties from GREET (Michael Wang 2012)

Fuel	BTU/gal listed in GREET
Conventional gasoline	116,090
Reformulated gasoline	113,602
Conventional diesel	128,450
Low-sulfur diesel	129,488
Ethanol	76,330
Fuel Property	**Share**
Ethanol in E10	0.095
Ethanol in E85	0.808

Table B3 Electricity emission factors (EF), in grams CO2 per kWh, for different generation fuel types from GREET 1 (Michael Wang 2012)

	Coal	Oil	Gas	Nuclear	Biomass	Hydro/Renewables/ Other
Upstream EF	56.5	142.5	140.1	14.5	67.1	0.0
Generation EF	1063.3	949.2	482.6	0.0	37.0	0.0
Total Average EF	**1119.8**	**1091.7**	**622.7**	**14.5**	**104.0**	**0.0**

Table B4 Percentage of electricity generation by power plants located in NERC Sub-regions and Census regions or divisions. Percentages in each row add to 100%. AKGD = ASCC Alaska Grid; AKMS = ASCC Miscellaneous; AZNM = WECC Southwest; CAMX = WECC California; ERCT = ERCOT All; HIMS = HICC Miscellaneous; HIOA = HICC Oahu; MROE = MRO East; MROW = MRO West; NEWE = NPCC New England; NWPP = WECC Northwest; NYCW = NPCC NYC/Westchester; NYLI = NPCC Long Island; RFCE = RFC East; RFCM = RFC Michigan; RFCW = RFC West; RMPA = WECC Rockies; SPNO = SPP North; SPSO = SPP South; SRMV = SERC Mississippi Valley; SRMW = SERC Midwest; SRSO = SERC South; SRTV = SERC Tennessee Valley; SRVC = SERC Virginia/Carolina

Associated Region	Divisions	NERC Sub-regions																									
		AKGD	AKMS	AZNM	CAMX	ERCT	FRCC	HIMS	HIOA	MROE	MROW	NEWE	NWPP	NYCW	NYLI	NYUP	RFCE	RFCM	RFCW	RMPA	SPNO	SPSO	SRMV	SRMW	SRSO	SRTV	SRVC
1 *Northeast*	1 New England	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	2 Middle Atlantic	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	9.8%	2.3%	21.3%	51.5%	0.0%	15.2%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
2 *Midwest*	3 East North Central	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	4.9%	1.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	14.5%	69.3%	0.0%	0.0%	0.0%	0.0%	10.4%	0.0%	0.0%	0.0%
	4 West North Central	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	56.9%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	20.6%	1.7%	0.0%	15.5%	0.0%	5.2%	0.0%
3 *South*	5 South Atlantic	0.0%	0.0%	0.0%	0.0%	0.0%	27.6%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	6.3%	0.0%	8.7%	0.0%	0.0%	0.0%	0.0%	0.0%	18.3%	0.3%	38.9%
	6 East South Central	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	3.3%	0.0%	0.0%	0.0%	4.9%	0.0%	31.6%	60.2%	0.0%
	7 West South Central	0.0%	0.0%	0.3%	0.0%	54.2%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	21.4%	23.7%	0.0%	0.0%	0.3%	0.0%
4 *West*	8 Mountain	0.0%	0.0%	48.4%	3.8%	0.0%	0.0%	0.0%	0.0%	0.0%	1.3%	0.0%	29.2%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	16.8%	0.0%	0.5%	0.0%	0.0%	0.0%	0.0%	0.0%
	9 Pacific	1.4%	0.4%	1.5%	51.8%	0.0%	0.0%	0.8%	2.1%	0.0%	0.0%	0.0%	42.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

Regions	AKGD	AKMS	AZNM	CAMX	ERCT	FRCC	HIMS	HIOA	MROE	MROW	NEWE	NWPP	NYCW	NYLI	NYUP	RFCE	RFCM	RFCW	RMPA	SPNO	SPSO	SRMV	SRMW	SRSO	SRTV	SRVC
1 Northeast	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	22.7%	0.0%	7.6%	1.8%	16.4%	39.8%	0.0%	11.7%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
2 Midwest	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	3.2%	20.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	9.6%	45.6%	0.0%	7.0%	0.6%	0.0%	12.1%	0.0%	1.8%	0.0%
3 South	0.0%	0.0%	0.1%	0.0%	19.4%	12.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	2.7%	0.0%	4.4%	0.0%	0.0%	7.7%	9.5%	0.0%	14.5%	12.8%	16.9%
4 West	0.7%	0.2%	24.5%	28.3%	0.0%	0.0%	0.4%	1.1%	0.0%	0.7%	0.0%	35.8%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	8.2%	0.0%	0.3%	0.0%	0.0%	0.0%	0.0%	0.0%

Table B5 Calculation of the percentage Ethanol Flex-Fueled Vehicles (FFV) consume gasoline vs. E85 (Derived from the EIA Annual Energy Outlook (2012b))

	2009	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**2031**	**2032**	**2033**	**2034**	**2035**
E85 consumption from all light-duty vehicles (in billions of gallons)	0.04	0.04	0.04	0.04	0.09	0.10	0.10	0.11	0.12	1.01	0.99	1.53	2.67	3.14	3.24	3.35	3.68	4.49	5.37	7.25	7.69	8.69	11.44	15.12	13.99	14.13	14.77
Gasoline consumption from Ethanol Flex Fuel vehicles (FFVs) (in billions of gallons)	5.84	6.52	7.17	8.05	8.92	9.77	10.56	11.31	12.03	12.13	12.87	13.16	13.01	13.37	13.95	14.51	14.92	14.98	15.01	14.21	14.42	14.24	12.79	10.64	11.94	12.29	12.25
Total fuel consumption from Ethanol FFVs (in billions of gallons)	5.88	6.56	7.21	8.09	9.01	9.86	10.66	11.43	12.15	13.14	13.86	14.70	15.68	16.51	17.20	17.86	18.60	19.47	20.38	21.46	22.12	22.93	24.24	25.76	25.93	26.42	27.02
Percentage of E85 consumed out of total fuel consumed for Ethanol FFVs	0.7%	0.6%	0.5%	0.5%	1.0%	1.0%	1.0%	1.0%	1.0%	7.7%	7.1%	10.4%	17.0%	19.0%	18.9%	18.8%	19.8%	23.1%	26.4%	33.8%	34.8%	37.9%	47.2%	58.7%	53.9%	53.5%	54.7%

Table B6 Emission factors, and the GREET model outputs used to derive them, for upstream (well-to-pump) and combustion (tank-to-wheel) for each liquid fuel type.
Note: LHV = lower heating value; EF = emission factor; g = grams; gal = gallon; mpg = miles per gallon; FE = fuel economy

		2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Low-level ethanol (LLE) blend vehicle GHG emissions	GREET model upstream output (Well-to-pump) in gCO_2eq/mi	90.9	89.9	89.0	88.1	87.3	86.4	85.6	83.7	82.0	80.3	78.6	77.1
	Upstream EF in g/gal	2034.4	2035.8	2040.4	2044.6	2048.5	2052.1	2055.3	2050.6	2045.8	2041.0	2036.1	2030.9
	GREET model combustion output (Tank-to-wheel) in gCO_2eq/mi	385.3	380.4	375.7	371.0	366.5	362.1	357.8	350.6	343.6	336.9	330.4	324.2
	Combustion EF in g/gal	8623.0	8618.1	8613.6	8609.1	8604.5	8600.0	8595.4	8585.1	8574.7	8564.4	8554.1	8543.7
LLE FE	GREET Model mpg in gallons gasoline equivalent	23.1	23.4	23.7	24.0	24.2	24.5	24.8	25.3	25.8	26.2	26.7	27.2
	Converted mpg	22.4	22.7	22.9	23.2	23.5	23.7	24.0	24.5	25.0	25.4	25.9	26.4
Diesel vehicle GHG emissions	GREET model upstream output (Well-to-pump) in gCO_2eq/mi	82.1	81.5	80.9	80.2	79.6	78.9	78.3	76.8	75.3	73.9	72.5	71.2
	Upstream EF in g/gal	2563.0	2576.4	2588.4	2600.0	2611.2	2621.9	2632.2	2634.9	2637.6	2640.1	2642.5	2644.6
	GREET model combustion output (Tank-to-wheel) in gCO_2eq/mi	330.4	327.0	323.0	319.0	315.2	311.4	307.7	301.5	295.5	289.7	284.2	278.8
	Combustion EF in g/gal	10313.5	10337.3	10338.8	10340.3	10341.7	10343.2	10344.7	10347.2	10349.8	10352.3	10354.9	10357.5
Diesel FE	GREET Model mpg in gallons gasoline equivalent	27.7	28.1	28.4	28.8	29.1	29.4	29.8	30.3	30.9	31.5	32.1	32.6
	Converted mpg	31.2	31.6	32.0	32.4	32.8	33.2	33.6	34.3	35.0	35.7	36.4	37.2
Dedicated ethanol vehicle (DE) GHG emissions	GREET model upstream output (Well-to-pump) in gCO_2eq/mi	7.5	3.6	1.8	0.1	-1.6	-3.2	-4.8	-6.5	-8.1	-9.7	-11.2	-12.7
	Upstream EF in g/gal	134.9	66.0	33.9	2.0	-29.8	-61.5	-93.1	-128.9	-164.5	-200.0	-235.2	-270.9
	GREET model combustion output (Tank-to-wheel) in gCO_2eq/mi	354.3	349.9	345.5	341.3	337.1	333.1	329.1	322.5	316.1	309.9	303.9	298.2
	Combustion EF in g/gal	6387.5	6386.9	6386.4	6385.9	6385.3	6384.8	6384.3	6383.2	6382.2	6381.2	6380.1	6379.1
DE FE	GREET model mpg in gallons gasoline equivalent	24.7	25.0	25.3	25.6	25.9	26.2	26.5	27.1	27.6	28.1	28.6	29.1
	Converted mpg	18.0	18.3	18.5	18.7	18.9	19.2	19.4	19.8	20.2	20.6	21.0	21.4
Reformulated gasoline (RFG) share of gasoline		0.5	0.5	0.5	0.6	0.6	0.6	0.7	0.7	0.8	0.9	0.9	1.0
Btu of gasoline per gallon (LHV)		114920	114846	114771	114696	114622	114547	114472	114298	114124	113950	113776	113602
Low-sulfur diesel share of diesel		0.8	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Btu of Diesel per gallon (LHV)		129280	129488	129488	129488	129488	129488	129488	129488	129488	129488	129488	129488

Table B7 Share of new conventional vehicle sales by class using the Annual Energy Outlook Reference Case (U.S. Energy Information Administration 2012b)

		2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Share by class for cars	Minicompact	1.0	0.9	1.2	1.0	1.0	1.1	1.0	1.0	1.0	1.0	1.0	1.0	1.0
	Subcompact	16.8	16.3	20.6	17.3	17.6	18.2	18.0	17.6	17.8	17.7	17.8	17.8	17.8
	Compact	22.9	22.6	27.7	23.7	24.2	25.1	24.9	24.4	24.5	24.5	24.4	24.5	24.4
	Midsize	40.3	40.5	35.2	39.4	38.9	38.1	38.2	38.9	38.6	38.7	38.7	38.6	38.7
	Large	16.6	17.1	12.9	16.2	15.8	15.2	15.5	15.6	15.6	15.6	15.7	15.6	15.7
	Two Seater	2.5	2.5	2.4	2.5	2.5	2.4	2.4	2.5	2.4	2.4	2.5	2.5	2.5
	Total Car	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Share by class for trucks	Small Pickup	4.8	4.9	3.9	4.7	4.5	4.4	4.4	4.4	4.4	4.4	4.5	4.5	4.5
	Large Pickup	21.5	21.2	21.7	21.4	21.4	21.3	21.1	21.2	21.2	21.1	21.3	21.4	21.3
	Small Van	1.7	1.6	2.1	1.7	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8
	Large Van	9.7	9.6	9.7	9.6	9.6	9.5	9.4	9.4	9.5	9.5	9.6	9.6	9.6
	Small Utility	34.2	34.3	33.7	34.3	34.2	34.2	34.4	34.4	34.4	34.5	34.2	34.2	34.2
	Large Utility	28.2	28.3	28.9	28.4	28.5	28.7	28.8	28.9	28.7	28.8	28.5	28.5	28.5
	Total Truck	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

		2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
Share by class for cars	Minicompact	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
	Subcompact	17.7	17.8	17.8	17.8	17.8	17.6	17.7	17.8	17.8	17.9	17.9	17.4	17.7	17.8
	Compact	24.4	24.5	24.4	24.5	24.4	24.3	24.4	24.4	24.4	24.5	24.5	24.0	24.3	24.4
	Midsize	38.7	38.6	38.7	38.6	38.7	38.8	38.7	38.7	38.7	38.6	38.6	39.2	38.8	38.7
	Large	15.7	15.6	15.7	15.6	15.7	15.8	15.7	15.6	15.6	15.6	15.6	16.0	15.8	15.6
	Two Seater	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.4	2.5	2.5	2.5	2.5
	Total Car	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Share by class for trucks	Small Pickup	4.6	4.5	4.5	4.5	4.6	4.6	4.6	4.5	4.5	4.5	4.5	4.6	4.6	4.6
	Large Pickup	21.3	21.4	21.3	21.3	21.4	21.3	21.4	21.4	21.4	21.4	21.4	21.3	21.4	21.4
	Small Van	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8
	Large Van	9.6	9.6	9.6	9.6	9.6	9.6	9.6	9.6	9.6	9.6	9.6	9.6	9.6	9.6
	Small Utility	34.2	34.2	34.2	34.2	34.2	34.2	34.2	34.2	34.2	34.2	34.2	34.2	34.2	34.2
	Large Utility	28.5	28.5	28.5	28.5	28.5	28.5	28.5	28.5	28.5	28.5	28.5	28.5	28.5	28.5
	Total Truck	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Table B8 EPA footprint class median calculation.

CAR Class	Micro*	Sub-Compact^	Compact	Midsize	Large
Footprint	35 36 37 38	39 40 41 42	43 44 45	46 47 48 49 50 51 52	53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80
Median	36.5	40.5	44	49	66.5
2-seater Median	40				

SUV Class	Small	Midsize #	Large
Footprint	35 36 37 38 39 40 41 42	43 44 45	46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80
Median	38.5	44	63

TRUCK Class	Small	Large
Footprint	35 36 37 38 39 40 41 42 43 44 45 46 47 48 49	50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80
Median	42	65

VAN Class	Depends on structure (Cargo vs. Mini van) [Small]	Depends on structure (Cargo vs. Mini van) [Large]
Footprint	35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57	58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80
Median	46	69

Note:

* This does not exist in the EPA modeling but is here for EIA modeling

^ This EPA considers anything below 43 to be Subcompact and does not have the 'Micro' category that EIA does

This does not exist in the EIA modeling but is here since it is a separate EPA category

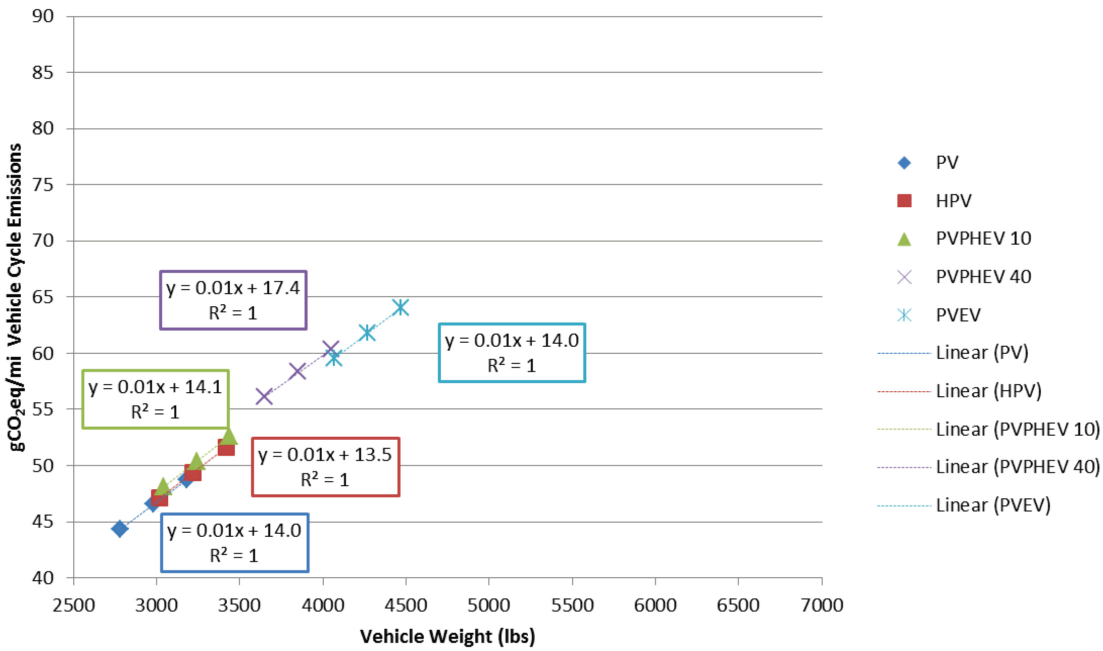

Figure B1 GREET 2 vehicle weight to vehicle production GHG emissions correlation for passenger cars (P) Note: HPV = Hybrid electric passenger vehicle; PVPHEV 10 = Passenger vehicle with 10 miles all-electric range; PVPHEV 40 = Passenger vehicle with 40 miles all-electric range; PVEV 10 = Battery electric passenger vehicle

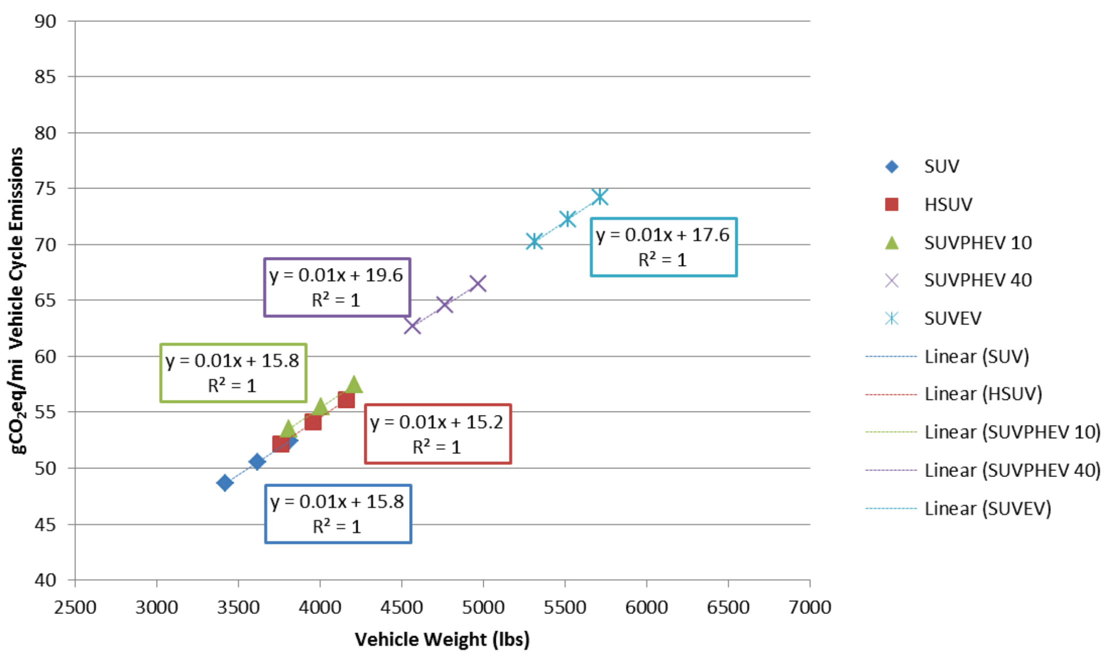

Figure B2 GREET 2 vehicle weight to vehicle production GHG emissions correlation for sport utility vehicles (SUV) Note: HSUV = Hybrid electric sport utility vehicle; SUVPHEV 10 = Sport utility vehicle with 10 miles all-electric range; SUVPHEV 40 = Sport utility vehicle with 40 miles all-electric range; SUVEV 10 = Battery electric sport utility vehicle

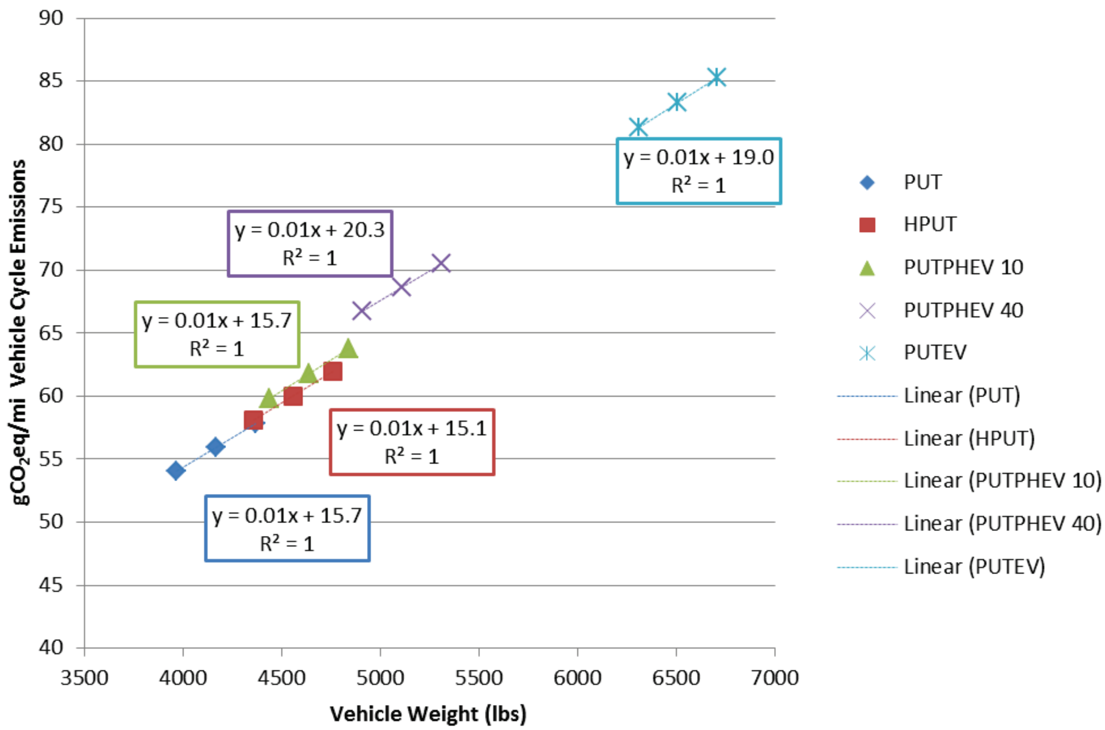

Figure B3 GREET 2 vehicle weight to vehicle production GHG emissions correlation for pick-up trucks (PUT) Note: HPUT = Hybrid electric pick-up truck; PUTPHEV 10 = Pick-up truck with 10 miles all-electric range; PUTPHEV 40 = Pick-up truck with 40 miles all-electric range; PUTEV 10 = Battery electric pick-up truck