Environmental assessment of plug-in hybrid electric vehicles using naturalistic drive cycles and vehicle travel patterns: A Michigan case study.

by

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Abstract

Plug-in hybrid electric vehicles (PHEVs) use grid electricity as well as on-board gasoline for motive force. These multiple energy sources make prediction of PHEV energy consumption challenging and also complicate evaluation of their environmental impacts. This thesis introduces a novel PHEV energy consumption modeling approach and compares it to a second approach from the literature, each using actual trip patterns from the 2009 National Household Travel Survey (NHTS). The first approach applies distance-dependent fuel efficiency and on-road electricity consumption rates based on naturalistic or real world, driving information to determine gasoline and electricity consumption. The second uses consumption rates derived in accordance with government certification testing. Both approaches are applied in the context of a location-specific case study that focuses on the state of Michigan. The two PHEV models show agreement in electricity demand due to vehicle charging, gasoline consumption, and life cycle environmental impacts for this case study. The naturalistic drive cycle approach is explored as a means of extending location-specific driving data to supplement existing PHEV impact assessments methods.

Acknowledgements

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List of Acronyms and Abbreviations

ANL	Argonne National Laboratory
ADJ	composite EPA-adjusted vehicle efficiency following method in Elgowainy et al. (2010) for power-split PHEV design configuration
AER	all electric range
CAFE	Corporate Average Fuel Economy
CO	carbon monoxide
CO_2	carbon dioxide
CD	charge depleting mode of PHEV operation
CH_4	methane
CS	charge sustaining mode of PHEV operation
CV	conventional vehicle
CV_{AVG}	CV energy consumption model based on average efficiency estimate method using composite-adjusted (ADJ) values unless specified
CV_{NDC}	CV energy consumption model based on synthetic naturalistic drive cycle method
eGRID	Emissions & Generation Resource Integrated Database
EPA	Environmental Protection Agency
EPRI	Electric Power Research Institute
eSOC	energy state of charge
FOT	field operational test
GPS	global positioning system
GREET	Greenhouse gases, Regulated Emissions, and Energy use in Transportation
HHV	high heating value (129.25 MJ/gallon for gasoline)
HWFET	Highway Fuel Economy Test
IPCC	Intergovernmental Panel on Climate Change
MEFEM	Michigan Electricity, Fleet and Emissions Model
MJ	mega-joule
NHTS	National Household Travel Survey
NO_X	nitrogen oxide, NO and NO2
NREL	National Renewable Energy Laboratory
PECM	PHEV Energy Consumption Model
PHEV	plug-in hybrid electric vehicle
$PHEV_{AVG}$	PHEV energy consumption model based on average efficiency method using composite-adjusted (ADJ) values unless specified
$PHEV_{NDC}$	PHEV energy consumption model based on synthetic naturalistic drive cycle method
PM_{10}	particulate matter with diameter of 10 micrometers or less
PSAT	Powertrain System Analysis Toolkit
SAE	Society of Automotive Engineers
TFC	total fuel cycle
UDDS	Urban Dynamometer Driving Schedule
UF	utility factor
UMTRI	University of Michigan Transportation Research Institute
USLCI	U.S. Life Cycle Inventory
US06	supplemental test cycle representing aggressive driving behavior
VOC	volatile organic compounds

CHAPTER 1

Introduction

1.1 Rationale and description of research

Determining the environmental impacts of plug-in hybrid electric vehicles (PHEV) requires accurate prediction of vehicle energy consumption. PHEV fuel and electricity usage rates are sensitive to both driving distance and drive cycle, making it important to consider real-world conditions (Patil et al., 2009; R. B. Carlson et al., 2009). This study details a PHEV energy consumption prediction method that approximates driving behavior by applying naturalistic, or real-world, drive cycles to each trip in the vehicle's travel pattern.

Travel patterns describe daily vehicle trip profiles in terms of distance, time, and location. Drive cycles describe driving intensity or the nature of acceleration events during the course of a trip. In the case of PHEVs, travel patterns often dictate when battery charging occurs because charging may only be allowed at certain locations (Kelly et al., 2012; Peterson et al., 2011; Weiller, 2011). Battery charging influences the number of vehicle miles powered by grid electricity. Driving intensity determines the power demanded of the powertrain and directly affects vehicle energy consumption.

The Environmental Protection Agency (EPA) conducted vehicle testing using the city (UDDS) and the highway (HWFET) drive cycles until model year 2008, when drive cycles representing aggressive driving (US06), air-conditioner use (SC03), and cold temperature driving (cold FTP), were added to the test procedure to improve fuel economy prediction (EPA, 2012). For model years 2008-2011, vehicle manufacturers had two options for calculating fuel economies considered representative of real-world conditions. The first uses actual test data from the five EPA drive cycles to calculate adjusted city and highway fuel economy values. The second uses "mpg-based" formulas, equations 1 and 2, based on an industry-average for a particular group of vehicle models (EPA, 2012).

$$\textit{EPA adjusted city fuel economy} = 1/(0.003259 + 1.1805/\textit{UDDS}) \qquad (1)$$

$$\textit{EPA adjusted highway fuel economy} = 1/(0.001376 + 1.3466/\textit{HWFET}) \qquad (2)$$

The EPA applies a 43% city / 57% highway harmonic average to account for a shift in actual driving behavior (EPA, 2012), but the analysis of PHEVs remains challenging (Duoba et al., 2009; Silva et al., 2009) due to their dual operating modes: charge depleting (CD) or charge sustaining (CS). In CD mode, the power-split PHEV consumes both battery electricity and gasoline for propulsion. In CS mode, the vehicle consumes only gasoline (electricity is used, but not grid electricity, in CS mode the PHEV operates as a HEV). Depending on vehicle design and control strategy, a PHEV may operate in CD mode until the battery's energy state-of-charge (eSOC) is depleted to a predetermined level, or the CS and CD modes may be blended.

1.2 Review of previous work

Efforts to standardize a reporting procedure that combines CD and CS modes (SAE, 2010) typically rely on a utility factor (UF). UF refers to the estimated fraction of driving powered by electricity in a PHEV. Previous analyses utilize the UF to determine PHEV energy consumption but recognize that many factors impact its accuracy (Weiller, 2011; Elgowainy et al., 2010; EPRI, 2007). Several complications in estimating electrically driven miles with UF include variations in driving conditions, driver characteristics, vehicle configuration and control strategy (Elgowainy et al., 2010; EPRI, 2007).

Naturalistic drive cycles are synthesized by applying stochastic processes to extracted real-world driving information and then validating them. This study uses driving information collected in Southeast Michigan. The representativeness of the synthetic naturalistic drive cycles is validated (Lee & Filipi, 2010), and the method applied to PHEV analyses (Lee et al., 2011a; Patil et al., 2009; Patil et al., 2010), but the cycles are independent of vehicle type. Details of the synthesis and validation process are in Appendix 1 and Lee et al. (2011b).

This thesis offers a novel approach to PHEV energy consumption characterization through a method that does not rely on a utility factor or adjustments to federal test cycles. We track vehicle travel patterns from National Household Travel Survey data (NHTS, 2009) and charging information on a per-trip basis, similar to previous studies (Kelly et al., 2012; Peterson et al., 2011; Weiller, 2011), but deviate from previous work by measuring vehicle energy consumption for every NHTS trip based on the distance dependency of fuel economy, and on-road electricity consumption exhibited by synthetic naturalistic drive cycles. When applied in PHEV performance testing, the synthetic drive cycles elicit higher peak power results relative to those obtained using a sequence of standard test cycles (Patil et al., 2009;

Patil et al., 2010). When based on relevant drive cycle data and travel survey information, the naturalistic drive cycle method demonstrated here offers a supplement to current PHEV impact prediction approaches, and corroborates those results.

1.3 Organization of this thesis

The remainder of this thesis is organized as follows. Chapter 2 describes the method developed including the attributes of the vehicle energy consumption models. Chapter 2 also describes the input parameters to the simulation used in the environmental assessment. Chapter 3 describes the life cycle component of energy usage in the analysis and presents the results obtained. In chapter 4, these results are discussed, and conclusions are drawn. Appendices 3 and 4 describe the basis for choosing the values used in the naturalistic drive cycle and life cycle assessment portions of the analysis, respectively.

The research presented in this thesis has already been published in the following journal article: Marshall, B.M., J.C., Kelly, T.-K.Lee, G.A.Keoleian, Z. Filipi, "Environmental assessment of plug-in hybrid electric vehicles using naturalistic drive cycles and vehicle travel patterns: A Michigan case study" Energy Policy (2013) 58: 358 – 370.

CHAPTER 2

Methodology

2.1 Method overview

This analysis compares two midsize class PHEV energy consumption modeling methods. Both models use 2009 NHTS trip data to determine vehicle travel patterns. The specific NHTS data that the models use are the day of the week, a vehicle identifier, the start and end times for each trip, and the trip distance and destination. PHEVs are charged once daily upon arrival at home. The simulation steps through each trip in the NHTS travel day chronologically. When a trip is begun, electricity and gasoline are consumed at a rate based on the PHEV energy consumption model in simulation. An iterative process is used to guarantee that battery eSOC is the same at the beginning and end of a travel day. This approach is taken to prevent overstating the electrically driven miles due to the limitation of a single day of NHTS driving data per vehicle, and follows the procedure used for battery eSOC accounting in Kelly et al. (2012). That study suggests a variance of 7% in aggregate vehicle UF between assuming a fully charged battery, and ensuring the battery eSOC is equal at the beginning and ending of the day. Battery eSOC and gallons of gasoline consumed are calculated at the end of each trip and recorded for use with the next vehicle trip.

2.2 Vehicle energy consumption models

The two PHEV energy consumption models analyzed are based on a power-split PHEV design configuration simulated in Powertrain System Analysis Toolkit (PSAT) modeling software with the default vehicle control selected. The power-split architecture divides engine power between the vehicle's electrical and mechanical drive systems depending on the driving situation and control strategy. A conventional vehicle (CV) platform with performance similar to the PHEV is developed for energy consumption comparison. Parameters for the CV and PHEV energy consumption models analyzed are listed in Appendix 2 along with values for two PHEV models from the literature (Elgowainy et al., 2010) which are included as reference points for the vehicle efficiency adjustment to follow. Fuel economy values for the PHEV and CV models are reported in miles per gallon gasoline-equivalent (mpg_e) (EPA, 2011). Fuel consumption is reported in gallons per 100 miles (gal/100mi) and electricity consumption in kilowatt-hours per mile (kWh/mile).

2.3 Average vehicle efficiency method ($PHEV_{AVG}$)

The first PHEV energy consumption model, denoted $PHEV_{AVG}$, is characterized by the average fuel economy during operation in CS mode, the average fuel economy during operation in CD mode and the average per-mile electricity consumption on the road in CD mode. The $PHEV_{AVG}$ model is in one of four states at all times: parked and not charging, parked and charging, driving in CS mode, or driving in blended (engine and electric motor) CD mode. When driving, the $PHEV_{AVG}$ model operates in the blended CD mode until the usable battery is depleted. It then switches to CS mode until vehicle recharging occurs.

Calculation of the $PHEV_{AVG}$ fuel economy in CS mode begins with setting the battery eSOC to the lower limit and simulating the vehicle in PSAT under city and highway federal test cycles. The unadjusted fuel economies are 53.63 mpg_e (UDDS) and 54.17 mpg_e (HWFET). Applying the EPA harmonic average yields the composite-unadjusted CS fuel economy, 53.94 mpg_e (1.86 gal/100mi). Using the EPA "mpg-based" formulas (equations 1 and 2), adjusted city and highway fuel economies are 39.57 mpg_e and 38.11 mpg_e. The composite-adjusted (ADJ) fuel economy for the $PHEV_{AVG}$ in CS mode is 38.72 mpg_e (2.58 gal/100mi), a 0.73 gal/100mi increase in fuel consumption over the unadjusted composite value.

City and highway fuel economies in CD mode are generated by setting the battery eSOC to the upper limit and allowing the vehicle to run under the test cycles in blended mode, resulting in 495.98 mpg_e (UDDS) and 362.19 mpg_e (HWFET), which are consistent with findings from an Argonne National Laboratory (ANL) study using a similar vehicle (Elgowainy et al., 2010). The unadjusted composite CD mode fuel economy using the EPA harmonic average is 409.71 mpg_e. On-road electricity consumption values are determined by setting the battery eSOC to its upper limit and allowing only the electric components (battery and motor) to propel the vehicle, resulting in 0.219 kWh/mile (UDDS) and 0.230 kWh/mile (HWFET). The unadjusted composite electricity consumption rate, 0.225 kWh/mile, is the arithmetic average of the two test cycle results.

Because the power-split design that the $PHEV_{AVG}$ is based on blends engine and motor operation, actual on-road fuel and electricity consumption is dependent on many factors including the aggressiveness of the drive cycle, vehicle control, and the power rating of the vehicle's components (Elgowainy et al., 2010; Duoba et al., 2009). In a life cycle analysis of PHEVs, ANL follows the EPA "mpg-based" method for fuel economy adjustment in CS mode operation. For blended CD mode operation in the power-split PHEV design, the

ANL study suggests that many adjustments to fuel and electricity consumption are possible due to the above factors (Elgowainy et al., 2010).

We examine the adjustment methods adopted by ANL for two PHEV designs to aid in developing a CD mode fuel and electricity consumption adjustment approach for the $PHEV_{AVG}$ simulation. The first ANL model we consider is a power-split PHEV design with 20 miles of all-electric range (AER), described in Appendix 2, and designated PHEV20. Although the PHEV20 is only 119kg lighter than the $PHEV_{AVG}$, its electric drive components are significantly smaller than those of the $PHEV_{AVG}$. This relatively undersized electric drive suggests that the PHEV20 will be more likely to use additional gasoline to meet the demand of real-world conditions than the $PHEV_{AVG}$ design. The second ANL PHEV design we consider is a series PHEV with a 40-mile AER, designated PHEV40, also described in Appendix 2. The series PHEV design mechanically decouples the engine from the wheels but requires a larger drive motor and battery to maintain performance (Freyermuth et al., 2008).

Figure 1, adapted from the ANL study, shows the fuel and electricity consumption for ANL's PHEV20 operating in a blended CD mode, and their method for adjusting consumption to be representative of real world conditions. It also presents a proposed adjustment method for the $PHEV_{AVG}$ model that will make it more consistent with real world operation. To simplify the explanation, we present the $PHEV_{AVG}$ and PHEV20 models as having the same unadjusted, blended CD mode operating point with regard to fuel and electricity consumption, this is only to illustrate the process. In the figure, ANL dictates that the PHEV20 model receives no electricity consumption adjustment. ANL assumes that real-world driving conditions increase CD mode fuel consumption for the PHEV20 by the amount calculated using the "mpg-based" formulae equations 1 and 2 (arrow a-A). The ANL series PHEV40 does have an adjustment to its electricity consumption. That vehicle model has a relatively large battery and electric motor capacity that can meet the additional loads typical of real-world driving, with ancillary power provided by the engine. ANL applies a 42.8% increase to the CD mode electricity consumption of the series PHEV40 model (Elgowainy et al., 2010).

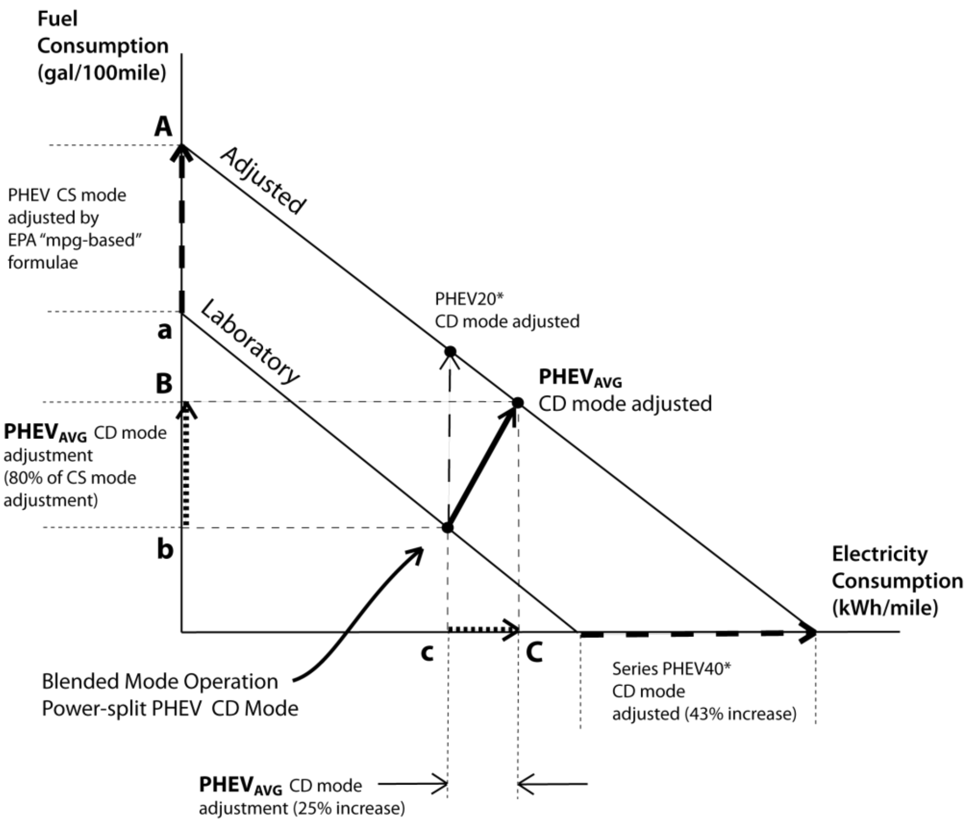

Figure 1. On-road adjustment of blended CD mode operation in the $PHEV_{AVG}$ energy consumption model. The $PHEV_{AVG}$ CD mode adjustment method is illustrated with CD mode adjustment of two PHEV models from the literature (Elgowainy et al., 2010)*. The diagram is adapted from Elgowainy et al. (2010) and Duoba et al. (2009). Adjustments are not shown to scale.

The ANL study assumed no increase in electricity consumption for their power split PHEV adjustment because their motor (65.7kW) was relatively small compared to their engine (59.8kW). In this study, the motor (110 kW) is much larger than the engine (62 kW) so the adjusted energy consumption is assumed to draw significant power from the motor. We adjust electricity consumption of the $PHEV_{AVG}$ upward 25% from its unadjusted level (arrow c-C). The result is 0.281 kWh/mile for the adjusted $PHEV_{AVG}$. Similarly, because of the larger motor, the $PHEV_{AVG}$ CD mode fuel consumption adjustment will be less than the full $PHEV_{AVG}$ CS mode fuel consumption adjustment. Instead of adjusting the CD mode fuel consumption upward by the full CS mode adjustment amount (arrow a-A), we adjust it upward by 80% of that amount (arrow b-B) (0.58 gal/100mi, in this case). This value is added to the unadjusted-composite $PHEV_{AVG}$ CD mode fuel consumption (0.24 gal/100mi) to arrive at the adjusted composite value, 0.83 gal/100mi. This corresponds to a $PHEV_{AVG}$ CD mode fuel economy of 121 mpg_e, which is used in the PHEV energy consumption model comparison and life cycle analysis.

Table 5. Summary of estimated energy consumption for $PHEV_{AVG}$.

	CS mode		CD mode		
Unadjusted	**mpg_e**	**gal/100mi**	**mpg_e**	**gal/100mi**	**kWh/mile**
$PHEV_{AVG}$ (UDDS)	53.6	1.86	495.98	0.20	0.219
$PHEV_{AVG}$ (HWFET)	54.2	1.85	362.19	0.28	0.230
$PHEV_{AVG}$ (US06)	36.6	2.74	59.11	1.69	0.333
$PHEV_{AVG}$ composite	53.9	1.86	409.2	0.24	0.225

	CS mode		CD mode		
Adjusted	**mpg_e**	**gal/100mi**	**mpg_e**	**gal/100mi**	**kWh/mile**
$PHEV_{AVG}$ composite (ADJ)	38.7	2.58	121	0.83	0.281

2.4 Naturalistic drive cycles method ($PHEV_{NDC}$)

The second energy consumption model, $PHEV_{NDC}$, uses fuel economy and on-road electricity consumption rates generated in PSAT through the application of synthetic naturalistic drive cycles to the power-split PHEV with parameters shown in Appendix 2. Similar to the $PHEV_{AVG}$, the $PHEV_{NDC}$ model operates in one of four states: parked and not charging, parked and charging, driving in CS mode, or driving in blended CD mode. The $PHEV_{NDC}$ drives in blended CD mode until the usable battery is depleted. $PHEV_{NDC}$ then switches to CS mode until vehicle recharging occurs.

The naturalistic drive cycle data used in this study exist for ten trip distances ranging from 4.88 miles to 40.97 miles for fuel economy values, and 4.88 miles to 35.03 miles for on-road electricity consumption rates, according to the synthesis process and the extracted real-world data (Lee et al., 2011b). The estimated CS mode fuel economy for the $PHEV_{NDC}$ model is shown as a function of trip distance in Figure 2 and compared to the $PHEV_{AVG}$ value. $PHEV_{NDC}$ fuel economy values for trip distances lower than the range of synthetic drive cycle data are calculated based on a linear fit to the data and an estimated endpoint of 52.5 mpg_e (1.90 gal/100mi) at zero miles. Fuel economy for longer trips is calculated according to a logarithmic fit to the data that levels off to 32.5 mpge (3.07 gal/100mi) at 1440 miles. We observe lower fuel efficiency at longer distances due to the higher cruising speed and more aggressive acceleration events under real-world driving. The PSAT-based PHEV model is optimized for fuel efficiency under relatively mild and moderate driving conditions, represented by federal certification cycles. The higher aggressiveness of the long distance driving patterns causes significant fuel efficiency losses because the PHEV is operating beyond its fuel efficient performance points.

PSAT-generated on-road electricity consumption rate values for CD mode operation of the $PHEV_{NDC}$ model are shown in Figure 3 compared to the $PHEV_{AVG}$ value. The on-road electricity consumption rate is approximated at 0.220 kWh/mile for zero miles and the data is linearly extrapolated for longer trip distances. Estimated fuel consumption in CD mode operation of the $PHEV_{NDC}$ model is shown in Figure 4 and compared to the $PHEV_{AVG}$ value. $PHEV_{NDC}$ fuel consumption value at zero miles is approximated at 0.43 gal/100mi (230.0 mpg_e). CD mode fuel consumption is assumed to logarithmically approach 1.43 gal/100mi (70.0 mpg_e) at 1440 miles.

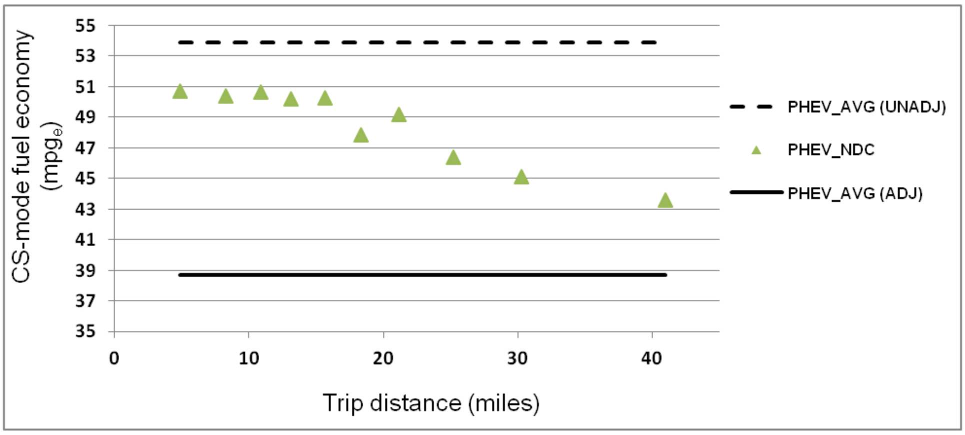

Figure 2. $PHEV_{AVG}$ and $PHEV_{NDC}$ estimated fuel economies during CS mode operation. $PHEV_{NDC}$ values are generated through the application of synthetic naturalistic drive cycles. Both energy consumption models are based on the PSAT power-split PHEV model parameters in Appendix 2.

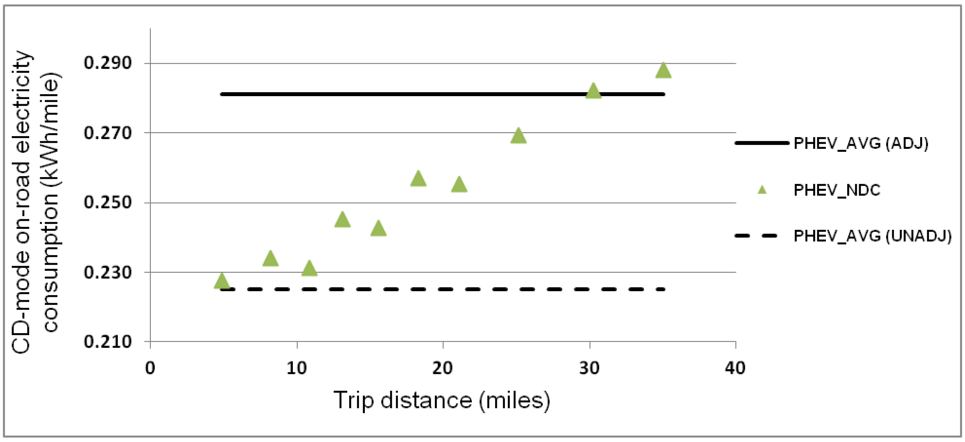

Figure 3. $PHEV_{AVG}$ and $PHEV_{NDC}$ estimated on-road electricity consumption rates during CD mode operation. $PHEV_{NDC}$ values are generated through the application of synthetic naturalistic drive cycles. Both energy consumption models are based on the PSAT power-split PHEV model parameters in Appendix 2.

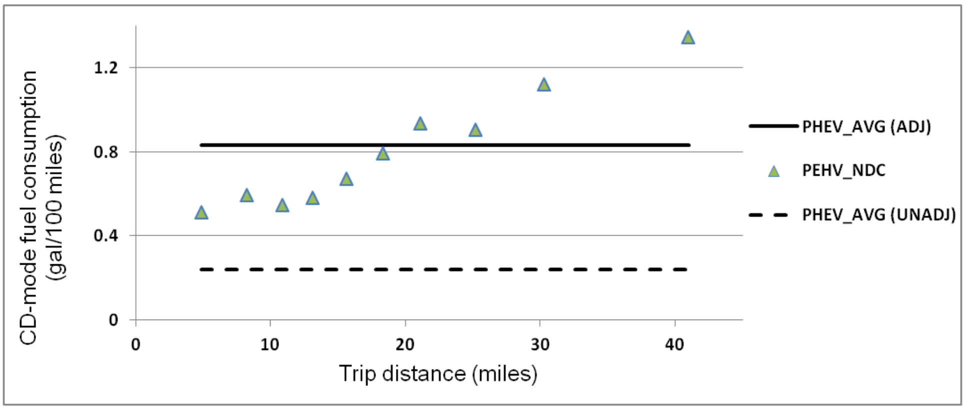

Figure 4. $PHEV_{AVG}$ and $PHEV_{NDC}$ estimated fuel consumption during CD mode operation. $PHEV_{NDC}$ values are generated through the application of synthetic naturalistic drive cycles. Both energy consumption models are based on the PSAT power-split PHEV model parameters in Appendix 2.

2.5 Conventional vehicle models (CV_{AVG} and CV_{NDC})

Measuring conventional vehicle (CV) impacts relative to the PHEV requires an energy consumption model comparable to the one used for the PHEV. The PSAT CV model is developed by starting with a two-wheel drive vehicle platform with the same resistance coefficients and frontal area as the PHEV models. See Appendix 2 for CV model parameters. The CV mass is adjusted downward 150kg from the PHEV mass to account for the absence of the battery and electric drive components. The engine is sized at 128 kW to produce the same 0.0 to 60.0 mph time as the PHEV (8.9 seconds). The CV model is simulated according to the $PHEV_{AVG}$ and $PHEV_{NDC}$ energy consumption estimation methods. CV_{AVG} corresponds to the $PHEV_{AVG}$ method that develops average consumption rates from federal test cycles. CV_{NDC} corresponds to the $PHEV_{NDC}$ method that uses naturalistic drive cycle inputs to estimate energy consumption. The CV_{AVG} calculation begins with PSAT-generated city and highway fuel economies of 26.77 mpg_e (UDDS) and 41.42 mpg_e (HWFET). The composite-adjusted (ADJ) fuel economy for the CV_{AVG} is derived following the same procedure as the $PHEV_{AVG}$ fuel economy. **Error! Reference source not found.** lists both unadjusted and adjusted CV_{AVG} fuel economies for the city (UDDS) and highway (HWFET) test cycles and the composite values. The estimated CS mode fuel consumption for the CV_{NDC} model is shown as a function of trip distance in Figure 5 and compared to the $PHEV_{AVG}$ value.

Table 2. Summary of estimated energy consumption for CV_{AVG}

Unadjusted	**mpg_e**	**gal/100mi**	**Adjusted**	**mpg_e**	**gal/100mi**
CV_{AVG} (UDDS)	26.8	3.73	CV_{AVG} (UDDS)	21.1	4.73
CV_{AVG} (HWFET)	41.4	2.41	CV_{AVG} (HWFET)	29.5	3.39

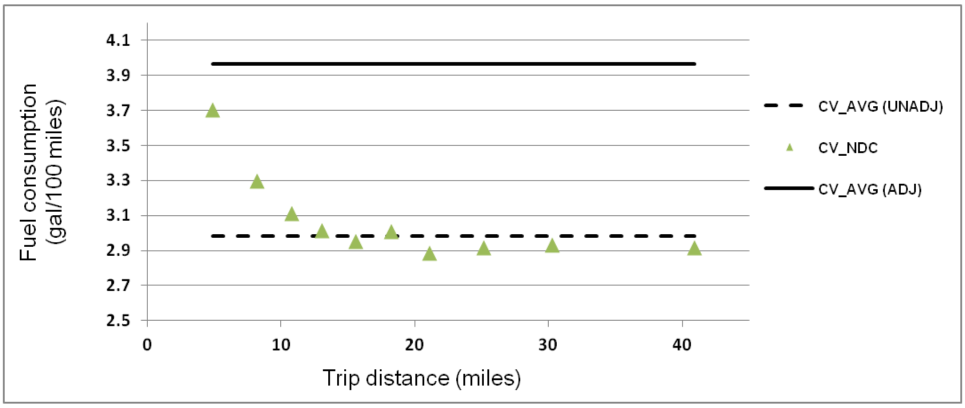

Figure 5. CV_{AVG} and CV_{NDC} estimated fuel consumption. CV_{NDC} values are generated through the application of synthetic naturalistic drive cycles. Both energy consumption models are based on the PSAT CV model parameters in Appendix 2.

2.6 PHEV environmental impact assessment

The PHEV and CV energy consumption models are evaluated for total fuel cycle energy, greenhouse gas, and criteria air pollutant impacts following a method from previous work on PHEV deployment in Michigan (Keoleian et al., 2011).

Figure 6 shows a high-level diagram of the simulation used in the analysis. To aid in the examination of the different vehicle energy consumption models, this study: (1) constrains PHEV fleet infiltration to ten percent of on-road midsize class vehicle totals in Michigan (2009); (2) analyzes each vehicle model ($PHEV_{AVG}$, $PHEV_{NDC}$, CV_{AVG}, or CV_{NDC}) separately; (3) eliminates NHTS data with anomalously high single vehicle travel days (>1440 miles); (4) considers a single PHEV charging scenario (at-home only, charge upon arrival); and (5) models 2009 Michigan electricity generation assets assuming zero electricity is imported from outside the state during the simulation period.

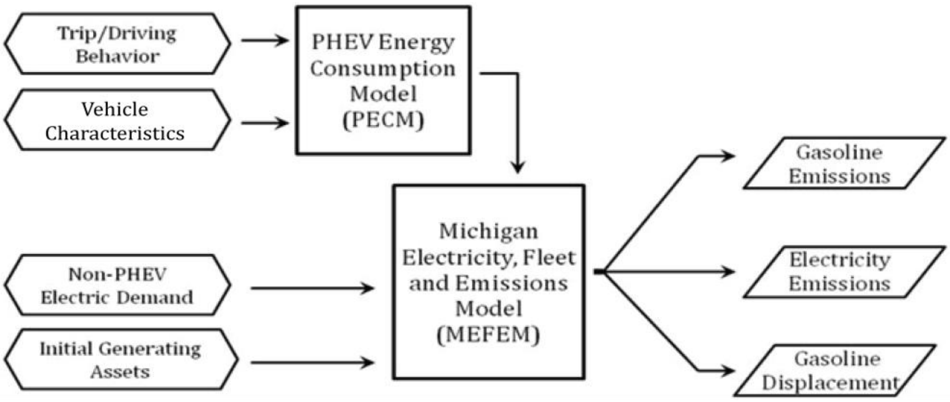

Figure 6. Schematic of the simulation used in the PHEV environmental impact assessment. PECM and MEFEM are independent models in the simulation.

The PHEV Energy Consumption Model (PECM) is used to determine PHEV fleet average electricity use, and PHEV and CV fleet average gasoline use. The Michigan Electricity, Fleet and Emissions Model (MEFEM) characterizes the Michigan electricity grid and simulates the dispatch operation of generation assets on an hourly basis. The impact on hourly electricity demand and system emissions from the PHEV demand is evaluated from the outputs of MEFEM. PECM groups NHTS trip data by vehicle to track on-road energy consumption and battery charging, then aggregates the charging profile and gasoline consumption for all vehicles and normalizes the total using statistical weights provided in the NHTS. This provides a representative hourly charging pattern for the PHEVs. The process is repeated for each day of the week, and daily profiles are then combined to create a charging profile for the PHEV energy consumption model under test. Figure 7 shows the one-week charging profile for the $PHEV_{NDC}$ and $PHEV_{AVG}$ models. MEFEM replicates weekly charging profiles over the course of a year assuming that there are no seasonal changes in driving patterns. The charging profile approximates the aggregate charging behavior of the fleet of PHEVs in Michigan when multiplied by the number of on-road midsize vehicles.

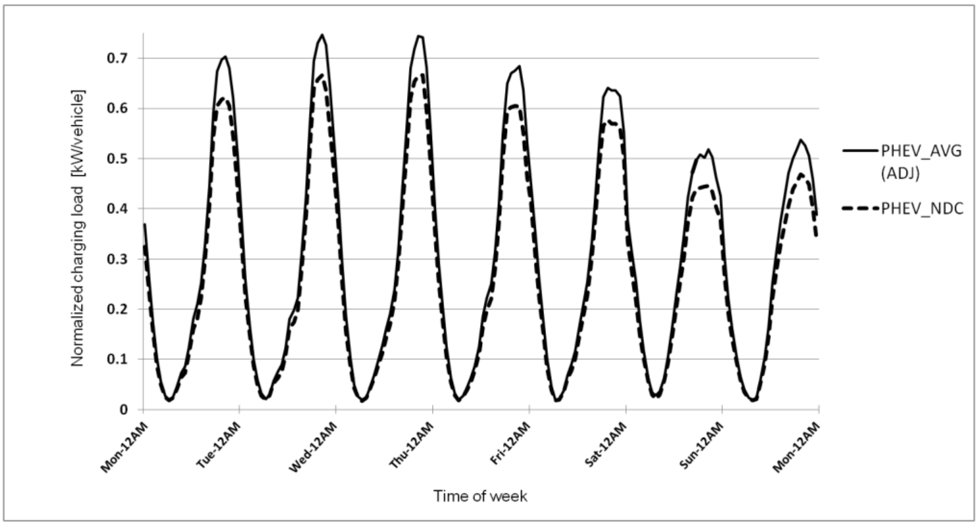

Figure 7. Normalized hourly charging pattern for the test fleet of $PHEV_{AVG}$ and $PHEV_{NDC}$ energy consumption models. Vehicle charging occurs at-home only, upon arrival.

Within MEFEM, Michigan power plants are based on those reported in the EPA's Emissions and Generation Resource Integrated Database (eGRID) 2005 database (EPA, 2012). Once the total electric demand is quantified and all plants are defined, plants are dispatched to serve the hourly load. Any deficit is assumed to be met from outside the state as imported energy. This is modeled as an additional plant with its own emissions factors equivalent to the average rate for the Midwest Independent System Operator (MISO) region. The simulation uses a dispatch order of generating assets based on their cost of generation. Cost is calculated for each power plant, and the plants are sorted from least to most expensive to generate electricity. The dispatch model determines the power output of every power plant for every hour, which is used to determine total electrical system emissions. The model has been verified by comparison with real data suggesting an aggregate underestimation of SOx (~10%), an overestimation of CO2 (~7%), and no consistent variance in NOx. Model details are available in Keoleian et al. (2011).

MEFEM provides energy use and emissions estimates due to vehicle fuel consumption and electricity generation. The model tracks total fuel cycle (TFC), or well-to-wheels, energy, greenhouse gases, and criteria pollutants. Total fuel cycle energy includes extraction, processing and transportation of fuels as well as the energy embodied in the fuel used to propel the vehicle, whether that energy comes from gasoline combustion in the engine, or from electricity stored in the battery and converted in the vehicle motors. MEFEM applies upstream energy factors from SimaPro software, using the U.S. Life Cycle Inventory (USLCI) database (NREL, 2009). Appendix 3 discusses assumptions made in USLCI and

SimaPro-based estimates. Equations 3 and 4 outline the life cycle components of energy usage for the PHEV and CV energy consumption models using a high heating value (HHV) for gasoline and vehicle production (Samaras & Meisterling, 2008) and battery production (Sullivan & Gaines, 2012) energy estimates from the literature.

Life cycle components of PHEV energy use = (3)

vehicle production energy + battery production energy +
electricity used to charge battery +
*(PHEV gasoline combustion and gasoline upstream energies)*HHV of gasoline*

Life cycle components of CV energy use = (4)

vehicle production energy +
*(CV gasoline energy + gasoline upstream energy)*HHV of gasoline*

The fuel cycle emissions from electricity generation are comprised of both combustion emissions and upstream emissions. Combustion refers to the emissions released when the fuel is burned, while upstream refers to the emissions released while mining, drilling, refining the fuel, and transporting the fuel from the extraction site to point of combustion. Upstream emissions factors for electricity are from the USLCI via SimaPro software. Combustion emissions factors associated with the generation of electricity are from two sources: eGRID and USLCI. Upstream and combustion emissions factor used are listed in Appendix 3.

Emissions from vehicular gasoline consumption are also comprised of both combustion and upstream emissions. The emission factors for both combustion and upstream activities used in this model are taken from the Greenhouse gases, Regulated Emissions and Energy use in Transportation (GREET) 1.8c model (Wang, 2009). The total fuel cycle energy factors for gasoline are also derived from GREET 1.8c using the default inputs**.**

To calculate emissions, MEFEM applies the combustion and upstream emissions factors to the energy generation output of each dispatched power plant. It applies plant specific emissions factors for fuel combustion from eGRID and national average emissions factors from USLCI for the upstream emissions of each fuel type to the electricity generated for each power plant at each hour. The outputs are the annual and hourly upstream and combustion emissions for each power plant. Equations 5 and 6 outline the life cycle components of greenhouse gas emissions (kg CO_2e) for the PHEV and CV energy consumption models using vehicle production (Samaras & Meisterling, 2008) and battery production (Sullivan & Gaines, 2012) emissions estimates from the literature.

Life cycle components of PHEV emissions = (5)

vehicle production emissions + battery production emissions +
(electricity generation and upstream emissions) +
(PHEV gasoline combustion and gasoline upstream emissions)

Life cycle components of CV emissions = (6)

vehicle production energy +
(CV gasoline combustion and gasoline upstream emissions)

This study tracks life cycle energy and emissions using a marginal allocation method. Marginal allocation compares the energy or emissions from a baseline Michigan electricity demand scenario with no PHEVs to that of a scenario with PHEV fuel and electricity demand added to that baseline. The difference is allocated to PHEVs. The effect of this allocation method is that the total fuel cycle energy and life cycle emissions of only the additional electricity that had to be used to provide power for charging are assigned to PHEVs (Keoleian et al., 2011).

CHAPTER 3

Results

3.1 Life cycle energy use

Total fuel cycle, or use-phase, components for the $PHEV_{NDC}$ and $PHEV_{AVG}$ consumption methods are presented in Table 6 along with the CV results. TFC energy calculations use national average energy factors applied to each 2009 Michigan power plant's combustion or generation, added to the combustion energy, to give the plant's total fuel cycle energy consumption. See Appendix 3 for details. The $PHEV_{NDC}$ energy consumption method indicates 11.3% less fuel cycle energy use per mile and 1.4% more electrically driven miles relative to the average efficiency method. This result follows from a $PHEV_{NDC}$ model that is more efficient in fuel economy than the $PHEV_{AVG}$ for all NHTS trip distances (

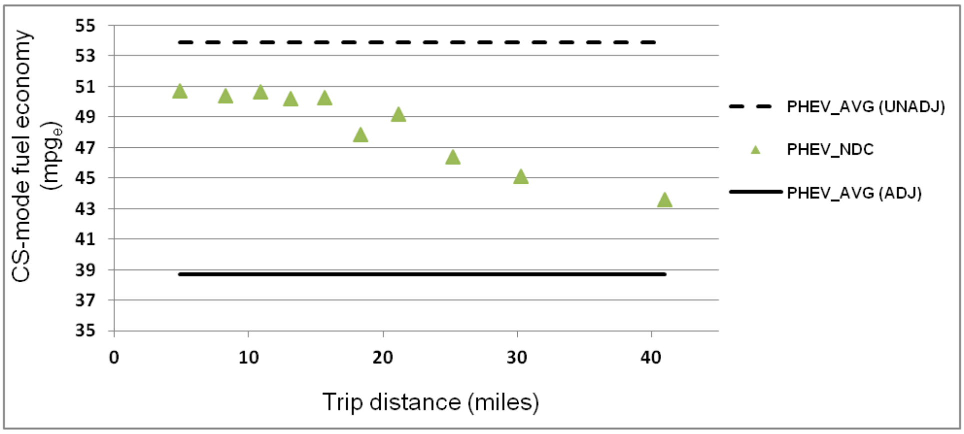

Figure 2), and more efficient in on-road electricity consumption for all distances less than approximately 30 miles (Figure 3). The CV_{NDC} and CV_{AVG} models show a similar difference in fuel cycle energy use per mile. The CV_{NDC} is more fuel-efficient than the CV_{AVG} model for all NHTS trip distances greater than approximately 4 miles (Figure 5).

Table 6. Total fuel cycle (use phase) components of energy for PHEV and CV consumption models.

	Marginal Electricity (MJ)	Gas (gal)	Gas Upstream (gal)	NHTS miles		TFC energy use per mile (MJ/mi)
				Electric	Gasoline	
$PHEV_{AVG}$	2.15E+10	1.70E+08	4.91E+07	5.38E+09	4.86E+09	4.87
$PHEV_{NDC}$	2.01E+10	1.45E+08	4.18E+07	5.45E+09	4.79E+09	4.32
% Diff.	-6.6%	-14.9%	-14.9%	1.4%	-1.5%	**-11.3%**
CV_{AVG}	0	4.06E+09	1.17E+09	0	1.02E+11	6.61
CV_{NDC}	0	3.23E+09	9.32E+08	0	1.02E+11	5.25
% Diff.	0%	-20.6%	-20.6%	0%	0%	**-20.6%**

Full life cycle energy impacts include battery and vehicle production as well as fuel cycle components. Battery production energy for both PHEV models are based on a 190 kg Li-ion battery (Appendix 2) using data from Sullivan and Gaines (2012). Vehicle production energy use for all models are based on Samaras and Meisterling (2008). Figure 8 compares the $PHEV_{NDC}$ and $PHEV_{AVG}$ and associated CV models on life cycle energy impacts in MJ/mile and adds a life cycle energy estimate for a CV model from Elgowainy et al. (2010) for reference. $PHEV_{AVG}$ impacts are shown for the composite-adjusted (ADJ) values and the three standard test cycle efficiencies listed in Table 5. $PHEV_{NDC}$ is 11.3% lower in life cycle energy use per mile than the $PHEV_{AVG}$ (ADJ) and 24.3% lower than the $PHEV_{AVG}$ (US06) aggressive driving estimate. $PHEV_{NDC}$ is 24.0% and 19.7% higher than the $PHEV_{AVG}$ city (UDDS) and highway (HWFET) test cycle estimates, respectively. CV_{NDC} is 20.6% lower than the CV_{AVG} model in life cycle energy use. The higher estimated fuel efficiency of the CV_{NDC} model relative to the CV_{AVG} model for all NHTS trip distances (Figure 5) indicates the reason for the difference in TFC energy use among the CV models.

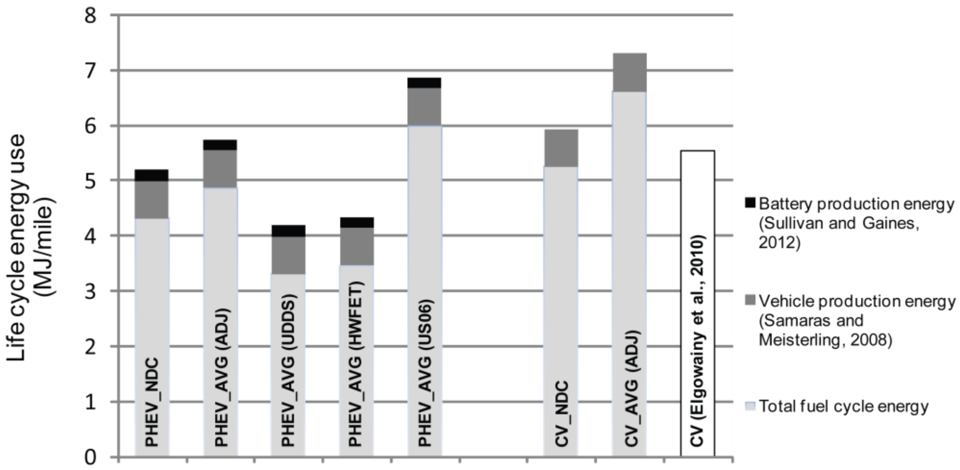

Figure 8. Per-mile life cycle energy impacts for PHEV consumption models using the naturalistic drive cycle method and the average efficiency method. The average method is calculated with EPA ADJ values and three standard test cycle values. CV impacts for each method are also shown. PHEV energy use is based on the 2009 Michigan electricity grid.

3.2 Life cycle emissions

To assess the impact of the PHEV models on greenhouse gas (GHG) emissions, three GHGs are tracked: Carbon Dioxide (CO_2), Methane (CH_4), and Nitrous Oxide (N_2O). The PHEV and CV results are presented in CO_2 equivalents (CO_2e) per mile using global warming potentials as defined by the IPCC Fourth Assessment Report (IPCC, 2007). Table 7 lists the components of total fuel cycle, or use-phase, greenhouse gas emissions for the PHEV and CV naturalistic drive cycle models relative to the corresponding average efficiency model.

Table 7. Total fuel cycle (use phase) components of greenhouse gas emissions for PHEV and CV energy consumption models.

	Electricity Generation (kg CO2e)	Electricity Upstream (kg CO2e)	Gasoline Combustion (kg CO2e)	Gasoline Upstream (kg CO2e)	NHTS miles		GHG emissions per mile (kgCO2e/mi)
					Electric	Gasoline	
$PHEV_{AVG}$	1.83E+09	1.65E+08	1.52E+09	3.86E+08	5.38E+09	4.86E+09	0.38
$PHEV_{NDC}$	1.71E+09	1.54E+08	1.29E+09	3.28E+08	5.45E+09	4.79E+09	0.34
% Diff.	-6.6%	-6.6%	-14.9%	-14.9%	1.4%	-1.5%	**-10.6%**
CV_{AVG}	0	0	3.89E+10	9.22E+09	0	1.02E+11	0.44
CV_{NDC}	0	0	2.88E+10	7.32E+09	0	1.02E+11	0.35
% Diff.	0%	0%	-20.6%	-20.6%	0%	0%	**-20.6%**

As is the case with energy use, the fuel cycle emissions component is the largest contributor to life cycle emissions. One important factor in the levels of GHG emissions due to PHEVs is the energy source of electricity production. Samaras and Meisterling estimate 295 gCO_2e/mile life cycle GHG emissions when using a PHEV model with energy consumption parameters similar to the $PHEV_{AVG}$ (HWFET) model. They model a 2008 U.S. average grid scenario with a GHG intensity for electricity of 670 gCO_2e/kWh (Samaras & Meisterling, 2008). The $PHEV_{AVG}$ (HWFET) life cycle emissions in the current study are 354 gCO_2e/mile when charging from a 2009 Michigan grid that is 66% coal-fired generation, with a life cycle GHG intensity of 793 gCO_2e/kWh (using eGRID 2009 Michigan power plants, a 5.82% Eastern T&D loss, and GREET 2012 upstream emission factors). A comparison of results from this study and results from the Samaras and Meisterling study (US average grid) shows that, for a similar vehicle, per-mile GHG emissions increase by 20% when the GHG intensity of the grid increased by 18.3%. Within the fuel cycle emissions estimate are the GHGs due to the upstream production and generation of electricity. The simulated Michigan grid (793 gCO_2e/kWh) emissions from electricity-related fuel cycle components are 195 gCO_2e/mile. By comparison, EPRI (2007) estimates 175 gCO_2e/mile for a projected 2010 "Old Coal" electrical grid with a carbon intensity of 575 gCO_2e/kWh.

Figure 9 shows that driving behavior is also an important factor in life cycle GHG emissions. The $PHEV_{NDC}$ estimate for life cycle GHG emissions (413 gCO_2e/mile) is 8.9% lower than the $PHEV_{AVG}$ (ADJ) estimate (454 gCO_2e/mile). The $PHEV_{AVG}$ models using city (UDDS) and highway (HWFET) estimated consumption rates have life cycle GHG impacts per mile 20.5% and 16.6% below the $PHEV_{NDC}$ emissions, respectively. Under the aggressive driving schedule (US06), the $PHEV_{AVG}$ model estimate is 22.5% higher than the $PHEV_{NDC}$ estimate.

The per-mile GHG emissions from the two ANL PHEV models (PHEV20 and PHEV40), examined in the adjustment procedure above, are also shown in Figure 9 using an electrical grid scenario comparable to the 2009 Michigan grid. Elgowainy et al. (2010) simulate a 2015 Illinois electrical grid dominated by coal-fired power plants (67% of capacity) as one of the scenarios with the PHEV20 and PHEV40 models. The 2009 Michigan grid had 66% generation from coal-fired power plants (eGRID, 2012). Controlling for grid intensity, we see a marked increase in per-mile GHG emissions from the $PHEV_{NDC}$ and $PHEV_{AVG}$ models relative to the ANL PHEV models. The ANL CV model shows close agreement to the $PHEV_{NDC}$ in per-mile GHG emissions.

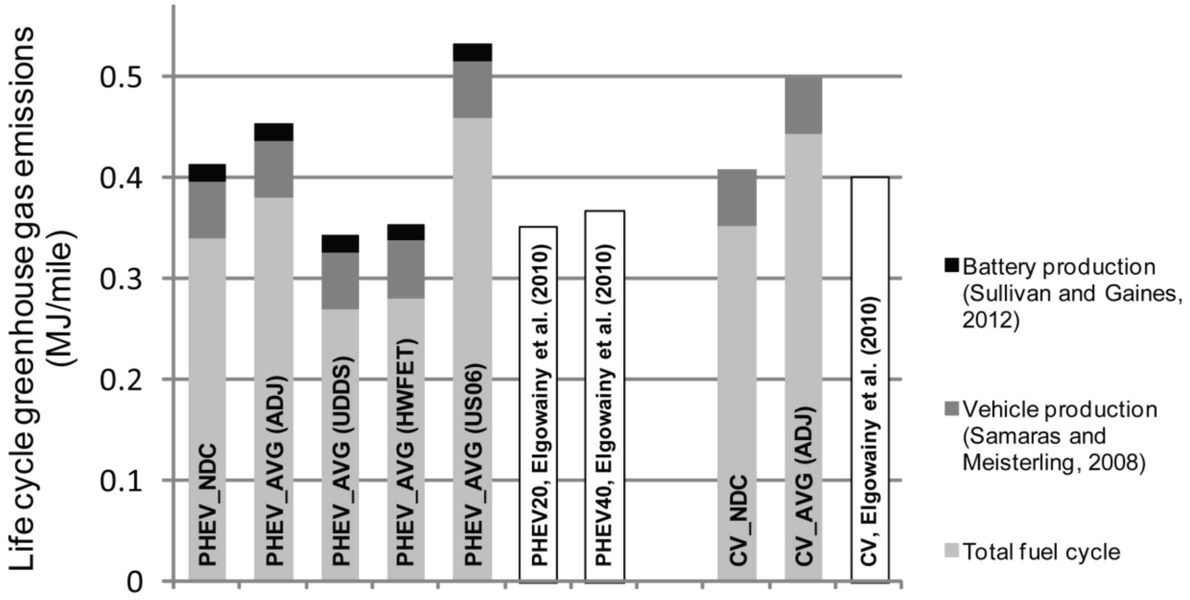

Figure 9. Per-mile life cycle GHG emissions for PHEV consumption models using the naturalistic drive cycle method and the average efficiency method. The average method is calculated with EPA-adjusted values and three standard test cycle values. CV impacts for each method are also shown. Two PHEVs and a CV model from the literature are compared (Elgowainy et al., 2010). PHEV emissions are based on the 2009 Michigan electricity grid.

Implications to Michigan air quality involve the examination of other atmospheric emissions beyond GHGs. MEFEM calculates the emissions for five common air pollutants, defined as criteria pollutants by the EPA and regulated under the Clean Air Act as follows: Carbon Monoxide (CO), Nitrogen Oxides (NO_X), Particulate Matter (PM_{10}), Ozone (which is created at ground-level via chemical reaction between NO_X and volatile organic compounds, VOCs), and Sulfur Dioxide (SO_X). Figure 10 summarizes the per-mile criteria pollutant emissions for both consumption models and vehicle types.

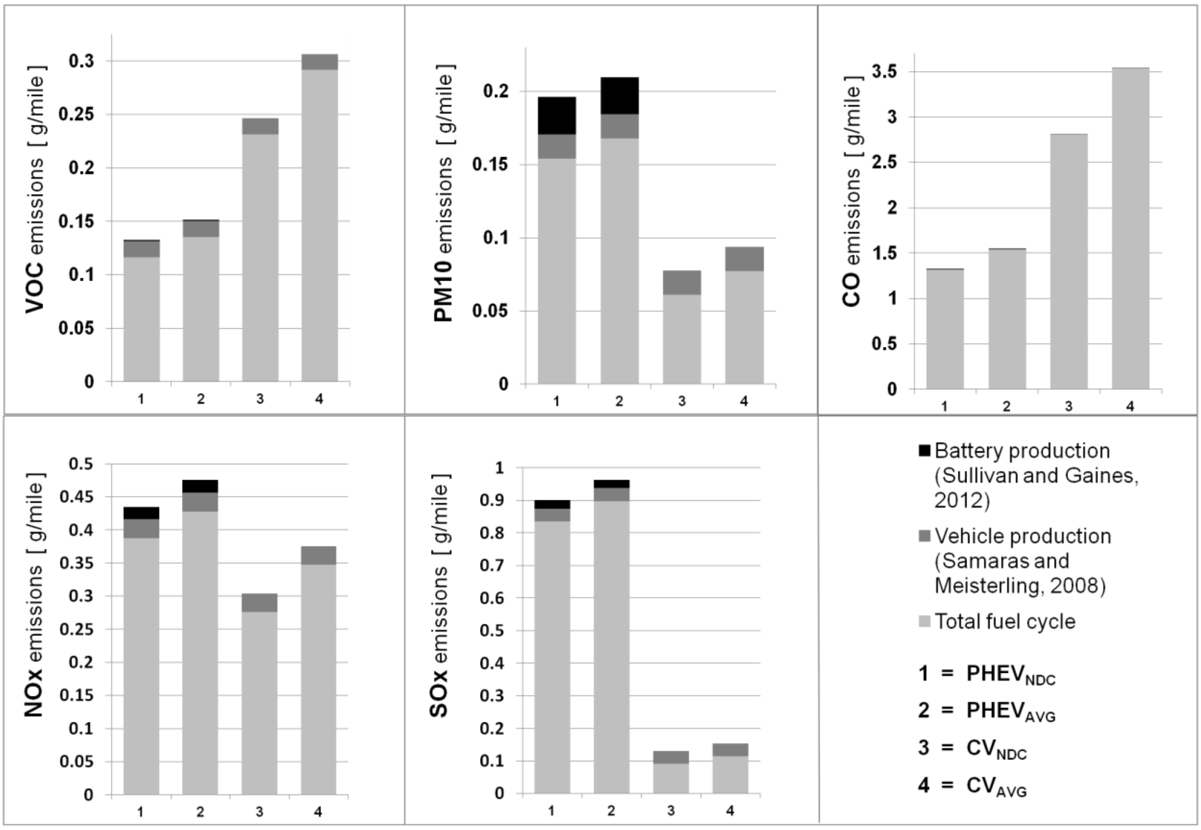

Figure 10. Fuel cycle criteria pollutant emissions per mile for PHEV and CV energy consumption models using the naturalistic drive cycle method and the average efficiency (ADJ) method. PHEV emissions are based on the 2009 Michigan electricity grid.

Previous studies have attempted to quantify the various externality costs associated with the above criteria pollutant emissions. Michalek et al. (2011) report pollutant valuations for a 'high damages' case based on urban areas. Thomas (2009) calculates an average for the five pollutants based on previous reports of urban air pollution costs. In both studies, sulfur dioxide (SO_2), the SO_X component of greatest concern, is used as the indicator for the larger sulfur oxides group. Cost valuations associated with rural air pollution are typically 10% of urban pollution costs (Thomas, 2009). Table 8 implies SO_2 and PM_{10} are the most critical pollutants from a cost standpoint. When these costs are combined with the emissions profiles in Figure 10, the importance of the source of electricity is emphasized. In the Michigan grid case, a 10% PHEV fleet infiltration suggests significant impacts due to these two pollutants.

Table 8. Urban air pollution costs per metric ton (2010 dollars)

	VOC	PM10	CO	NO_X	SO_2
Michalek et al. (2011)	$14,615	$23,416	$2,154	$8,375	$37,065
Thomas (2009)	$8123	$39,841	$1,814	$14,382	$23,658

CHAPTER 4
Discussion and Conclusions

4.1 Extension of the model

With the potential for widespread adoption of PHEVs in the future, policy makers will need access to accurate vehicle energy consumption data as well as energy and GHG intensity of regional grids to make informed decisions concerning the environmental impacts of future fleets. Synthetic naturalistic drive cycles provide a means of characterizing vehicle energy consumption by applying distance-dependent efficiencies to a vehicle's travel patterns. The potential of this approach to accurately predict PHEV vehicle energy consumption and therefore the environmental impacts of future PHEV fleets relies on location-specific considerations. Drive cycle measurements relevant to a particular region must be the basis for synthesis of drive cycles used in energy consumption analysis in that region. Travel survey data that capture actual household travel patterns in the region of interest are also required for the proposed method to accurately predict vehicle energy consumption. Knowledge of likely regional PHEV fleet penetration rates over time assists in accurate prediction of aggregate impacts.

The naturalistic drive cycles in this study are synthesized from driving data acquired in the Southeast Michigan area consisting of a mix of urban, suburban, and highway driving that can represent US Midwestern driving, but are not representative of driving patterns throughout the nation (Lee, et al., 2011). The 2009 NHTS dataset consists of a single day of travel information from households in various locations across the nation. This presents two constraints in replicating representative travel patterns for the Michigan-based study. The first constraint is the lack of multi-day travel information for individual households in the survey data. The second constraint is the study's substitution of national-based travel pattern information in the absence of a Michigan-based driving survey. These two limitations notwithstanding, the proposed methodology provides a foundation for enhancing the prediction of plug-in vehicle impacts. The synthetic naturalistic drive cycle approach can be extended to any region where location-specific driving cycle measurement data exist, and travel patterns are known via travel survey or other method. Candidate locations are increasing in number as new travel survey techniques and mature technologies such as global positioning systems (GPS) are used to obtain large sets of real-world drive cycles and travel patterns specific to a metropolitan area or similarly defined region (Gonder et al., 2007).

Related to the accuracy in characterizing local and regional travel patterns is the accurate characterization of vehicle charging patterns. A single charging scenario (at-home only, upon arrival) is assumed for the purpose of this analysis but a study using the same NHTS dataset and charging model developed scenarios to investigate the effects of battery size, charging location, charging rate, time of charging, and demographic variables to see how driver and household characteristics influence consumption patterns (Kelly et al., 2012). Those results are readily integrated with the proposed method to provide sensitivity analyses that could increase the accuracy of spatial and temporal battery charging estimation and thus PHEV energy consumption prediction.

PHEV market penetration rates are not independent of regional electrical grids. With a ten percent infiltration of $PHEV_{AVG}$ (ADJ) vehicles into the Michigan 2009 midsize vehicle fleet, the MEFEM model used in this study accommodates the additional 2.41E+10 MJ (6.69E+06 MWh) of marginal demand using existing 2009 Michigan grid assets with no electricity crossing state boundaries. Although the introduction of PHEVs at this volume is made without necessitating increases to Michigan's generating capacity, the possibility of PHEV infiltration in other locations where reserve margins for generation capacity may not be met highlights the importance of accurate characterization of PHEV energy consumption.

4.2 An alternative to existing methods

The synthetic naturalistic driving cycle methodology demonstrated in this study is an alternative to federal cycle testing procedures that currently form the basis for prediction of aggregate PHEV impacts. When enhanced through location-specific driving cycle measurement and travel survey information, PHEV assessment using the synthetic naturalistic drive cycles method offers a complementary environmental impact prediction to support current methods, and corroborates the EPAs current predications of PHEV impacts.

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APPENDIX 1: NATURALISTIC DRIVING CYCLE SYNTHESIS PROCEDURE

The synthesized naturalistic driving cycles are the representative cycles at each driving distance, not directly measured cycles. The synthesized cycles are constructed using the driving characteristics extracted from real-world driving data in Southeast Michigan collected by the University of Michigan Transportation Research Institute (UMTRI) by Field Operational Test (FOT) (LeBlanc et al., 2006). A total of 830 days 4409 trips were used for extracting the real-world driving patterns. The data include driving information sufficient for representing real-world driving patterns with respect to trip distance. Generalized real-world driving patterns include both local trips and free-way trips. Driving patterns are different with respect to driving distances. Thus, a driving distance based categorization is used to synthesize Southeast Michigan Urban/Suburban Driving Cycles in this paper (Lee et al., 2011).

The overall procedure is illustrated in Figure 11. The stochastic process combined with subsequent assessment procedures can construct driving cycles with verified representativeness. Initially, naturalistic driving cycles for the extraction of real-world driving information are selected within each concerning segment. Driving information is extracted in a form of velocity and acceleration matrices. The matrices relate current velocity and acceleration to future information. Every current state is mapped to the states in the next time step (i.e., future time step) one-to-one. A Markov Chain uses the information to synthesize the cycles.

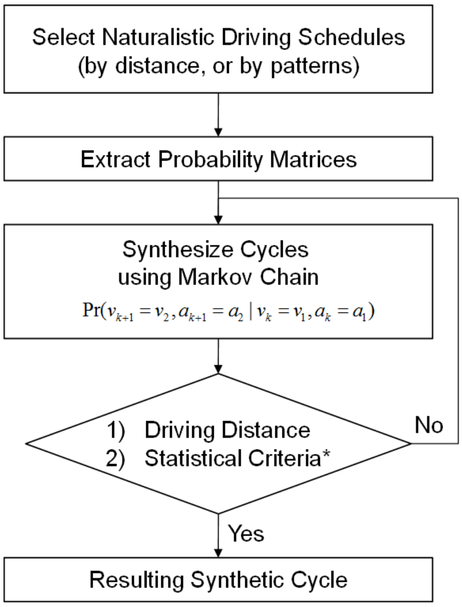

Figure 11. Naturalistic driving cycle synthesis procedure using Markov chain and statistical criteria (Lee et al., 2011).

In the synthesis procedure, a discrete-time Markov chain is used. This is a sequence of random variables X_1, X_2, X_3, ... with the Markov property expressed as:

$$\begin{aligned} &P(X_{n+1} = x_{n+1} \mid X_1 = x_1, X_2 = x_2, \cdots, X_n = x_n) \\ &= P(X_{n+1} = x_{n+1} \mid X_n = x_n) \end{aligned} \tag{7}$$

The set of possible values that the random variables X_n can take is the state space of the chain. The conditional probabilities, $p_{ij} = P(X_{n+1} = j|X_n = i)$, are transition probabilities. The probability used in the synthesis procedure is time-independent (or time-homogeneous). The sum of all probabilities leaving a state must satisfy:

$$\sum_j p_{ij} = \sum_j P(X_{n+1} = j|X_n = i) = 1 \tag{8}$$

To satisfy the Markov property in equation 7 such that future states depend only on the present states, an adequate number of states should be chosen. The required states are selected by investigating the simplified vehicle dynamics equation. Vehicle dynamics can be expressed by velocity and acceleration, and they are chosen as the states for the Markov chain. The transition probability matrix (TPM) is then generated in the form of a two dimensional matrix. The velocity and acceleration are discretized with the number of M and N, respectively. The conditional probability is expressed as:

$$P_{i,j,k+1|p,q,k} = P(v_{k+1} = v_i, a_{k+1} = a_i \mid v_k = v_p, a_k = a_q) \tag{9}$$

where *i and p*=1,2,…,*M*, *j and q*=1,2,…,*N*, and the overall TPM structure is shown in Figure 12.

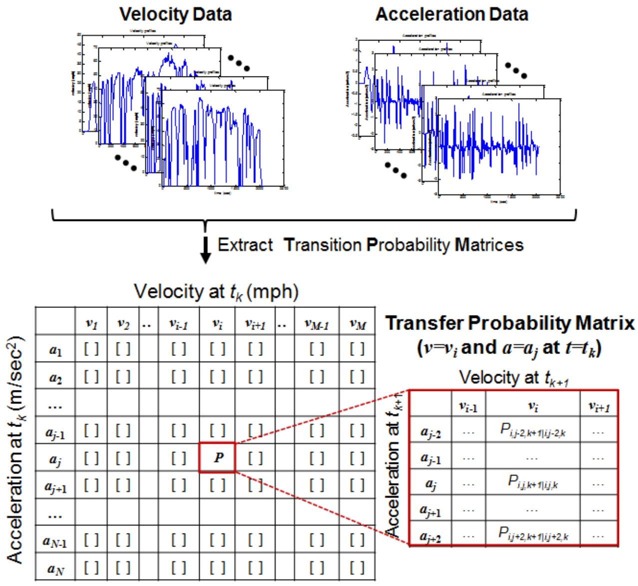

Figure 12. Illustration of the procedure to extract transition probability matrix (TPM) from real-world driving data

The driving distance distribution is regressed to find a smoothed probability density function (pdf) with the purpose of dividing driving data into several segments with the same probability depending on driving distance. Then, the driving cycle data are divided into ten segments having the same probability on the cumulative density function (cdf). A representative driving distance in each segment is selected as the mean value of the segment range. The selected one-way trip distances range from 4.78 to 40.71 miles (Lee et al., 2011)

The representativeness of synthesized cycles is verified by investigating statistically significant criteria. The statistical criteria are determined through generalized linear regression analysis as briefly described in Lee et al. (2011). Initially, a total number of 27 possible explanatory variables are identified and categorized into velocity related, acceleration related, driving-time and distance-related, and event related variables. Through the assessment of the inter-relationship between two variables, one is eliminated. Then, 16 variables remain as initial explanatory variables for the regression analysis. Generalized linear regression analysis is used to find the least number of significant variables. The analysis includes three assessment steps including a *t-test*, normal probability plots of the residuals, and histograms of the residuals. The least significant variables are eliminated one by one, given *t-test* results that indicate the ability of the reduced equation to represent the response variable with sufficient accuracy. The regression quality is subsequently assessed through normal probability plots of the residuals and histograms of the residuals. The final regression equations use statistically significant variables to establish bases for subsequent assessments of the representativeness of synthesized driving cycles. The significant explanatory variables are:

(1) Standard deviation of velocity (mph),
(2) Mean positive acceleration (m/s^2),
(3) Standard deviation of acceleration (m/s^2),
(4) Percentage of driving time under positive acc. (%),
(5) Percentage of driving time under negative acc. (%),
(6) Mean positive velocity (mph),
(7) Percentage of idle time (%),
(8) Number of stops/mile (1/mile).

APPENDIX 2: VEHICLE MODEL PARAMETERS

Vehicle Parameter	$PHEV_{AVG}$ and $PHEV_{NDC}$	Series PHEV40, 2015 medium case (Elgowainy et al., 2010)	Power-split PHEV20, 2015 medium case (Elgowainy et al., 2010)	CV_{AVG} and CV_{NDC}
Architecture	Power-split series/parallel	Series	Power-split series/parallel	2-wheel drive conventional
Vehicle Weight (kg)	1715	1792	1596	1565
Engine (kW)	62.0	70.7	59.8	128.0
Motor-generator 1 (kW)	110.0 (Rahman et al., 2011)	119.0	65.7	
Motor-generator 2 (kW)	55.0 (Rahman et al., 2011)	68.6	34.6	
Battery Type	Li-ion (Matthe et al., 2011)	Li-ion	Li-ion	
Usable Battery Energy (kWh)	8.0 (Matthe et al., 2011)	9.4	4.1	
Battery Power (kW)	>115 (Matthe et al., 2011)	144	53	
Battery Weight (kg)	190.0 (Matthe et al., 2011)			
AER (miles)	~35	40	20	
Drag Coefficient, C_d	0.28	0.28	0.28	0.28
Frontal Area (m^2)	~2.16	2.18	2.18	~2.16
Accessory Load (W)	200	230	230	200
0-60 mph Time (sec.)	8.9	~9.0	~9.0	8.9
Rolling Resistance	0.0088	0.0075	0.0075	0.0088
Final Drive Ratio				4.438

APPENDIX 3: TOTAL FUEL CYCLE METRICS

The outputs of the MEFEM model are life cycle emissions and energy use for both vehicle liquid fuel consumption and electricity generation. The model tracks criteria pollutants: CO, NO_X, PM_{10}, SO_X and VOCs, and greenhouse gases: CO_2, CH_4, and N_2O. It aggregates GHGs using Global Warming Potentials identified by the IPCC (IPCC, 2007). It also tracks total fuel cycle, or use-phase, energy for stationary and mobile energy generation sources. MEFEM applies emissions factors (kg/kWh of electricity or kg/gal of fuel) or an upstream energy factor (MJ/MMBtu of fuel input for electricity or MJ/gal of fuel) to the energy produced from each Michigan power plant and its heat rate, or to the gallons of gasoline consumed, to determine the total fuel cycle energy usage and emissions. Emissions factors are separated into both their upstream and combustion components so that they may be tracked separately. The manufacturing of plants is not included in the total fuel cycle accounting for electricity production. Battery manufacturing (Sullivan & Gaines, 2012) and vehicle manufacturing (Samaras & Meisterling, 2008) are added to account for full life cycle emissions and energy impacts.

Emissions Factors

The total emissions from electricity generation are comprised of both combustion emissions and upstream emissions. Combustion refers to the emissions released when the fuel is burned, while upstream refers to the emissions released while mining, drilling, refining the fuel, and transportation of the fuel from the extraction site to point of combustion. Upstream emissions factors for electricity are from the USLCI database (NREL, 2009) examined using SimaPro software. Each of the eight emissions types were determined in SimaPro by subtracting the "electricity, at power plant" process emissions from the sum of all life cycle emissions for these processes. The USLCI database does not specify a difference between $PM_{2.5}$ and PM_{10}, so all particulates are assumed to be PM_{10}. Some emissions data was not reported in the same categories. For example, sulfur dioxide was reported by some processes as SO_2, and some as SO_X. To compensate, these datasets were summed to get a total for each emission factor. Combustion emissions factors associated with the generation of electricity are from two sources: eGRID (EPA, 2012) and USLCI. The emission types provided by eGRID are NO_X, SO_X, CO_2, CH_4, and N_2O. These emissions are specific to each generating asset and are thus believed to be more representative than using average emissions data. National averages for CO, PM_{10}, and VOCs by source fuel type were used from the USLCI database using the same methodology as the upstream emissions because plant specific information was not available. It is assumed that national average upstream emissions for sub-bituminous coal are the same as those for bituminous coal. Table 9 shows a list of the eight emission factors used for 2009 Michigan power plants averaged by fuel type.

Table 9. Average emissions factors (kg/kWh) for 2009 Michigan power plants, by fuel type

	Sub-Bituminous Coal	Bituminous Coal	Oil	Natural Gas	Nuclear	Biomass	Landfill Gas
CO	0.30	0.30	3.74	0.49	0.01	0.09	0
NOX	1.58	2.07	12.63	0.49	0.07	1.19	0.81
PM10	0.78	0.78	0.16	0.05	0.06	0.04	0
VOC	6.90	6.90	2.42	5.68	0.23	0.30	0
SOX	3.57	5.33	94.68	6.04	0.23	1.54	0
CO2	1009.05	958.96	4033.69	551.85	10.84	163.99	0.01
CH4	1.84	1.84	1.22	3.31	0.03	0.31	0
N2O	0.02	0.02	0.06	0.00	0.00	0.04	0
GHGs	1060.05	1009.75	4082.60	635.11	11.54	185.21	0.01

The total fuel cycle emissions from vehicular gasoline consumption are also comprised of both combustion and upstream emissions. The gasoline emission factors for both combustion and upstream activities used in this model are taken directly from GREET1.8c (Wang, 2009) and shown in Table 10. Similarly, total fuel cycle energy factors for gasoline are derived from GREET1.8c using the default inputs. These factors are recorded in MJ/gal consumed. Vehicle manufacturing emissions and energy are not included in the total fuel cycle calculation but are included in life cycle emissions and energy accounting (Sullivan & Gaines, 2012; Samaras & Meisterling, 2008).

Table 10 Emission factors for one gallon of gasoline for both upstream and combustion processes.

	CO(g)	NOX(g)	PM_{10} (g)	SOX (g)	VOC (g)	CO2 (kg)	CH4 (g)	N2O (g)	GHG (kg)
Combustion	87.6	3.30	0.679	0.140	4.21	8.82	0.351	0.281	8.92
Upstream	1.62	5.45	1.26	2.738	3.14	1.94	12.5	0.131	2.27

Emissions Calculation

To calculate total emissions from electricity generation, MEFEM applies the combustion and upstream emissions factors to the energy generation output from the electricity dispatch algorithm. MEFEM generates emissions for each power plant using eGRID emissions factors (for NO_X, SO_2, CO_2, CH_4, and N_2O), its fuel type, and the amount of energy usage representing hourly electricity generation for the entire simulation year. It applies the eGRID and national average emissions factors for each fuel type, both upstream and combustion, to the electricity generated for each power plant at each hour. The outputs are the annual and hourly upstream and combustion emissions for each power plant.

Total Fuel Cycle Energy Factors

The factors for total fuel cycle energy were determined in SimaPro, using the USLCI database and Eco-Indicator 95 reporting methods. These factors include upstream energy from all coal, natural gas, crude oil, and uranium ore used in the entire fuel cycle of each power plant type. This upstream energy total was translated into a ratio of upstream energy (E_{UPS}) to either combustion energy (E_{COMB}) or generation energy (E_{GEN}). This ratio represents the national average for a total fuel cycle energy factor for each plant type. This factor, multiplied by a power plant's combustion or generation and added to the combustion energy gives that plant's total fuel cycle energy consumption. Wind, water and landfill gas generation are assumed to consume zero MJ of total fuel cycle energy, as facility manufacturing energy is not included in this model. Table 11 shows the upstream factors. Biomass and nuclear plants are based on generation energy, while fossil fuel plants are based on combustion energy.

Table 11. Upstream factors for 2009 Michigan power plants

	Coal	Natural Gas	Oil	Biomass	Nuclear
E_{UPS} / E_{COMB}	0.0217	0.05	0.027	N/A	N/A
E_{UPS} / E_{GEN}	N/A	N/A	N/A	0.0492	0.0207