# RATING THE ENVIRONMENTAL IMPACTS OF MOTOR VEHICLES: ACEEE'S GREEN BOOK® METHODOLOGY, 2011 EDITION

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The following document is an update of the ACEEE report, *Rating the Environmental Impacts of Motor Vehicles: ACEEE's Green Book® Methodology, 2004 Edition,* by James Kliesch.

*ACEEE's Green Book®: The Environmental Guide to Cars and Trucks* is a consumer-oriented publication that provides comprehensive environmental ratings for cars, vans, pickups, and sport utility vehicles, enabling consumers to comparison shop with the environment in mind. Each model is given a Green Score that accounts for both health-damaging air pollutants and climate-threatening greenhouse gas emissions. This technical report documents the methodology used to develop the ratings published in the 2011 edition of *ACEEE's Green Book®*, available online at www.GreenerCars.org.

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## ABSTRACT

Consumer education and other market-oriented approaches to improving the environmental performance of automobiles require information that is easy to understand and readily accessible. Such information can influence both buyer decisions and manufacturers' technology and product planning activities. To provide such information, ACEEE publishes *ACEEE's Green Book® Online,* an annual consumer-oriented guide providing environmental rating information for every new model in the U.S. light-duty vehicle market.

The environmental rating methodology for *ACEEE's Green Book®* is based on principles of life cycle assessment and environmental economics. The method is designed to be applicable given the limitations of data available by make and model in the U.S. market. The approach combines the impacts of regulated criteria pollutants with those of greenhouse gas emissions, covering the vehicle life cycle, upstream emissions, and manufacturing and disposal impacts. This report covers the data issues, key assumptions, and analysis methods used to develop the vehicle ratings for *ACEEE's Green Book®.* It summarizes the application of the methodology to the 2011 model year (MY), highlighting results for major classes and technology types, and identifies research needs for updating and refining the methodology.

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# INTRODUCTION

Public information and consumer education are important components of an overall strategy to address the environmental impacts of motor vehicles. Accessible information that rates car and light truck environmental performance can enable consumers to account for the environment in their purchasing decisions, help guide fleet programs and other market-creation initiatives, and assist automakers' efforts to market "greener" products.

To address these informational needs, since 1998 ACEEE has published an annual, consumer-oriented guide, now titled *ACEEE's Green Book®: The Environmental Guide to Cars and Trucks*, providing model-specific environmental information for the U.S. automotive market. This report covers the data issues, key assumptions, and analysis methods used to develop the ratings used in the model year 2011 edition of *ACEEE's Green Book®,* available online at greenercars.org. It summarizes the application of the methodology to the 2011 model year, highlights results for major classes and technology types, and identifies research needs for updating and refining the methodology. For background on the original development of this rating system and its policy context, see DeCicco and Thomas (1999a and 1999b).

## Rating Design Considerations

The production, use, and disposal of an automobile affect the environment in numerous ways. Impacts start with the extraction of raw materials that go into a vehicle and continue throughout materials conversion and fabrication processes, which involve many different industries. While a vehicle is in use, fuel consumption, driving, storage, and maintenance create air, water, and noise pollution as well as greenhouse gas (GHG) emissions. Disposal of worn parts (tires, batteries, motor oil, etc.) occurs throughout a vehicle's life. Finally the vehicle itself is discarded. Steel and other components can be, and increasingly are, reclaimed and recycled, but none of these processes are impact-free. An ideal rating system would incorporate all environmental impacts over a vehicle's life cycle.

Life cycle assessment (LCA) techniques provide a framework for systematically considering environmental impacts that can be used for eco-labeling of many products (EPA 1993a, 1993b). In recent years, the number of eco-labels has proliferated, including both government-sponsored programs as well as numerous private and nonprofit sector initiatives (WRI 2010). For U.S. light duty vehicles, EPA's newly finalized updates to the fuel economy label now provide information about GHG emissions and smog-forming pollutants (EPA/DOT 2011). However, EPA's label does not provide information about fuel cycle or vehicle life cycle impacts.

Table 1 illustrates the range of environmental concerns to be considered over the phases of a vehicle's life cycle and usage in the form of a product assessment matrix. Letter codes in the matrix cells show items covered in the methodology described here. Only the use phase is well covered because it is the only part lifecycle for which model-specific data are available.

Use phase energy- and air pollution-related effects represent most of a typical automobile's life cycle impacts. Argonne National Laboratory's GREET model estimates that the full fuel cycle GHG emissions of an average gasoline-powered automobile are 69% from fuel end use, 20% from fuel production and distribution, and 11% from vehicle materials and manufacturing processes (ANL 2006). Use phase shares vary for other pollutants, being high for carbon monoxide (CO) but lower for sulfur dioxide (SO2). With the phase-in of more stringent tailpipe standards in recent years, in-use emissions of criteria pollutants from gasoline-powered vehicles may have declined more rapidly than other life cycle emissions, reducing their percentage contribution to total impacts. Battery electric vehicles, appearing in the market today, have no in-use emissions and an entirely different profile of fuel upstream emissions.

**Table 1. Life Cycle Assessment Matrix for Estimating Motor Vehicle Green Ratings**

| **Environmental Concern** | **Phase of Product Life Cycle** | | | | | |
|---|---|---|---|---|---|---|
| | Materials Production | Product Manufacture | Product Distri-bution | Fuel Upstream | Product Use | End of Life |
| Air Pollution | C | C | | B | B | C |
| Energy Consumption | C | C | | B | A | C |
| Greenhouse Gas Emissions | C | C | | B | A | C |
| Land Contamination | | | | | | |
| Noise | | | | | | |
| Water Pollution | | | | | | |
| Worker/Community Health | | | | | | |
| Other Ecosystem Damage | | | | | | |

Status in the *ACEEE's Green Book*® methodology (blank cells indicate items not included):
A—Included explicitly, with good data quality and relatively high accuracy for discriminating among vehicles.
B—Included explicitly, but with lower level of data quality and relatively high uncertainties.
C—Included only indirectly, with very aggregate or uncertain data.

At present, only three types of relevant, independently verifiable data cover all makes and models: (1) vehicle emissions data, addressing most aspects of use phase air pollution; (2) vehicle fuel consumption data, addressing other aspects of use phase air pollution as well as energy use and GHG emissions; and (3) vehicle mass, addressing materials production, manufacturing and disposal impacts. For hybrid-electric and plug-in electric vehicles battery weight and composition may be available on a model-by-model basis as well. A rating system must integrate these data along with parameters for weighting the various items in order to provide a model-specific index of life cycle environmental impact.

### *Vehicle In-Use Emissions*

Automotive emissions of criteria air pollutants (six pollutants for which the Clean Air Act requires the EPA to set National Ambient Air Quality Standards) and their precursors are an important cause of environmental damage. These emissions occur at the tailpipe and from fuel evaporation and leakage. In the United States, new vehicles are required to meet emissions standards that regulate CO, hydrocarbons (HC), nitrogen oxides ($NO_x$), and particulate matter (PM), among other pollutants. (Until model year 2004, PM standards were enforced only for diesel vehicles, since gasoline vehicles have been considered to have negligible PM emissions.) Standardized emissions tests involve placing a vehicle on a chassis dynamometer and operating it over a simulated driving cycle while collecting samples of the exhaust. Tests are also made to detect fuel vapor leaks (evaporative emissions). Testing is the responsibility of automakers, who report the results to the U.S. Environmental Protection Agency (EPA) or the California Air Resources Board (CARB).

Historically, standard emissions tests have tended to underpredict in-use emissions substantially. Past data have revealed that lifetime average in-use emissions are two to four times higher than the nominal emissions standard levels in grams per mile (g/mi) to which the vehicles are certified (Calvert et al. 1993; Ross et al. 1995). The reliability of a vehicle's emissions control system (ECS), including engine operation which affects ECS performance, is a key determinant of the vehicle's lifetime real-world emissions. EPA's mobile source emissions models incorporate degradation factors and other parameters to predict average emissions rates over vehicle lifetimes. Earlier editions of the *Green Book* based in-use emissions on results from these models, which led to emissions factors that varied with vehicle category and fuel, even for vehicles certified to the same emissions standard. As discussed below and in Appendix D, in-use data for newer vehicles, with more sophisticated ECS and cleaner fuels, appears to be inadequate to justify continuation of this practice, and consequently Green Book 2011 ratings assume that vehicles emit at the levels of the standards to which they are certified. Substantial uncertainties remain, however, which is why Table 1 shows a "B" status for use-phase air pollution.

Since the fall of 2000, EPA has posted its own "Green Vehicle Guide" providing car and light truck emissions ratings information on the web (www.epa.gov/greenvehicles). While the *Green Book* ratings are derived from the same source data as EPA's ratings, there are a number of technical differences. Our approach is life cycle-based; EPA's is based separately on tailpipe emissions and fuel economy, which are dominant aspects of a vehicle's life cycle impact. The *Green Book* ratings weight various regulated pollutants using factors tied to public health epidemiological findings, while EPA assigns scores to bins without explicit reference to pollutant health burdens. Furthermore, the *Green Book* utilizes a different approach to presentation of results, combining all impacts into a single green score rather than presenting them separately as does EPA.

### *Fuel Consumption*

Vehicle fuel consumption and the fuel supply cycle produce emissions of both GHGs and criteria pollutants. Fuel supply cycle emissions, as well as certain in-use emissions, are essentially proportional to the quantity of fuel consumed. EPA derives estimates of fuel economy (miles per gallon, or mpg) for purposes of standards compliance from the same simulated city driving test that is used for meeting emissions standards (the FTP, or Federal Test Procedure), together with a simulated highway driving test. Vehicles are labeled for fuel economy based on these results together with additional test results, because the tests used to determine compliance with fuel economy standards are not adequate to represent actual on-road driving. Special requirements exist for the labeling of vehicles powered by electricity or other alternative fuels (FTC 1996, EPA/DOT 2011).

A vehicle's rate of fuel consumption drives its fuel supply cycle (or "upstream") impacts, which vary depending on the fuel and its source. For example, grid-connected electric vehicles, which may have zero vehicle emissions, entail a variety of power plant emissions and other impacts depending on how the electricity is generated. Average fuel supply cycle emissions factors (e.g., in grams of pollutant per British thermal unit [Btu] of fuel) for GHG and criteria emissions are fairly well known, based on national statistics. Thus, given fuel economy data, estimating a vehicle's fuel supply cycle impacts based on national averages enables discriminating among models powered by different fuels. However, as noted by the "B" ratings for fuel cycle impacts in Table 1, the discrimination ability is not as good as it is for on-vehicle, use-phase impacts for which certified model-specific data are available.

### *Vehicle Cycle Emissions*

Manufacturing impacts depend on materials use, where and how a vehicle and its components are built, and the environmental standards followed at each stage of the process. Automobile manufacturing involves a complex and fluid global supply chain, making it difficult to track the environmental pedigree of parts and materials. Impacts also depend on recycled content, since increasing the use of recycled materials can decrease impacts associated with virgin materials processing and product disposal. Data on manufacturing impacts and recycled content are not systematically available and the environmental reporting needed to provide meaningful estimates by make and model is largely undeveloped.

In 2007, Argonne National Laboratory released GREET 2.7 model, a vehicle-cycle model designed to examine the energy use and emissions associated with vehicle production and recycling and disposal. The model provides estimates of greenhouse gases and criteria pollutants related to vehicle and battery manufacturing and disposal for Internal Combustion Engine Vehicles (ICEVs), Hybrid-Electrics (HEVs) and Fuel Cell Vehicles (FCVs) (ANL 2006).

Vehicle weight is the only data relating to vehicle cycle impacts that is publicly available for every model on the market. GREET 2.7 results indicate that weight is in fact the dominant factor in materials production, manufacturing and end-of-life impacts. Hence a good sense of the variation of vehicle cycle impacts by model can be obtained by using vehicle weight as a GREET 2.7 input while using default values for the remaining parameters. As discussed further below, we also used model-specific battery weight and composition for hybrids and plug-in vehicles, because this data is available and can substantially influence the environmental impacts of these vehicles. Developing better methods for rating vehicles according to environment impacts from materials and parts production, assembly, and disposal remains an area for future work.

## Integrating Methodology

In essence, our rating system is based on performing a limited LCA for each car and light truck on the market. To formalize it and reduce the results to a single metric applicable to any vehicle, we define an *environmental damage index* (EDX). We define this index as a sum of damage functions, each based on attributes associated with the life cycle of the vehicle and its fuel:

$$\text{EDX} = \sum_i \text{Damage}(\text{Impact}_i)$$

In principle, impacts could include any of those listed in Table 1. A valuation based on environmental economics would use monetized damage functions so that the EDX expresses an expected life cycle environmental cost of the vehicle. We have adopted such a framework while noting its limitations. Dollar-based damage functions can never capture the full value to society of human life, health, and quality of life; ecological effects; and the moral dimensions of environmental harms.

That being said, and restricting the damages considered to GHG and criteria pollution emissions during the vehicle's life cycle and associated fuel cycle, a monetized environmental damage function reduces to:

$$\text{EDX} = \sum d_{ij} e_{ij}$$

where i is an index over emission species (air pollutants, including greenhouse gases), j is an index over locations of emissions, $d_{ij}$ is an environmental damage cost (e.g., cents per gram), and $e_{ij}$ is the quantity of emissions averaged over a vehicle's operational life (e.g., grams per mile). The damage index so defined represents environmental impacts averaged over vehicle lifetime travel distance and the units can be given in cents per vehicle mile (¢/mi).

# CHARACTERIZATION OF IMPACTS

Given the data availability as noted above, the relation $\text{EDX} = \sum d_{ij} e_{ij}$ can be calculated on the basis of vehicle emissions, fuel cycle emissions, and emissions factors based on vehicle and battery mass (for embodied energy and environmental impacts).

## In-Use Emissions

Some vehicle emissions are regulated and others are not. We estimate both. Regulated emissions include CO, non-methane organic gases (NMOG), HC, $NO_x$ and particulate matter smaller than 10 microns ($PM_{10}$). These emissions depend largely on the emissions standard to which a vehicle is certified and its fuel. Hydrocarbon (HC) vapors may be reported as volatile organic compounds, NMOG or in other ways, depending on the technique and use of the measurement (EPA 2010). We estimate evaporative HC emissions as a function of both fuel consumption and emissions certification level.

The pollutants that are not directly regulated for motor vehicles but are incorporated in our rating system are sulfur dioxide ($SO_2$), methane ($CH_4$), nitrous oxide ($N_2O$), and carbon dioxide ($CO_2$); the last three of these will be regulated beginning in the 2012 model year. We estimate all four pollutants as a function of fuel type and consumption rate, independently of the emissions standard. We do not at this time explicitly estimate emissions of air toxics, though these have a large overlap with regulated emissions.

### *Regulated In-Use Criteria Emissions from Vehicles up to 8,500 lb. GVW*

Tailpipe and evaporative emissions are regulated for cars and light trucks under both Federal and California vehicle emissions programs. The 2011 Green Book methodology assumes that, on average over the life of a vehicle, regulated tailpipe pollutants are emitted at the level of the intermediate useful life (50,000-mile) standards to which the vehicle is certified.

Historically, real-world testing has shown average emissions over the life of a vehicle substantially in excess of the standards to which it is certified (EPA 2003). This is in part because the certification values pertain to performance over the Federal Test Procedure (FTP) cycle, which does not fully replicate real-world operation. In particular, operation at high speed, at low temperature, and using the air conditioner are not reflected in the bin certification levels. Some of these "off-cycle" emissions are captured by the Supplemental Federal Test Procedure (SFTP); but the corresponding supplemental standards are far above the standards defining the emissions bins and presumably are too high to provide a reasonable estimate of average emissions. Another reason lifetime average emissions may exceed the standards to which they are certified is that emissions deteriorate with time and mileage, and vehicles are driven further on average than the full useful life of 120,000 miles assumed for purposes of emissions standards (DOT 2006).

In light of these considerations, Green Book methodology in prior years estimated real-world average emissions rates in excess of standards, in many cases several-fold higher. To what extent this is appropriate for new vehicles today is unclear, however. Improvements in emissions control systems and in on-board diagnostics may mean that average emissions over the life of a vehicle are substantially closer to their respective certification standards. Data on these newer vehicles emissions are limited, however, and in particular data on real-world performance of low-bin gasoline vehicles and bin 5 diesels are not available. While emissions rates well in excess of emissions standards undoubtedly occur, we do not have a solid basis on which to distinguish among vehicles certified to a given standard based on, e.g., differing vehicle class or fuel. Given that comparative environmental impacts are more fundamental to Green Book ratings than absolute impacts are, we will base our ratings on the level of standards to which vehicles are certified until more data becomes available. For a more extensive discussion of this matter, see Appendix F.

For 2011 ratings, we used 50,000-mile standards to represent average lifetime emissions rates of $NO_x$, NMOG, and CO for vehicles certified to Tier 2 bins 5 through 8 or to California standards LEV II or ULEV II. PM standards and standards for all pollutants for bins 1 through 4 and for SULEV are defined at 120,000 miles only. Following the approach of earlier Green Book methodology, we scaled down full-life certification values of $NO_x$, NMOG, and CO for vehicles in bins 2 through 4 and SULEV, and used these values in place of 50,000-mile standards. PZEVs, which meet the same tailpipe standards as SULEVs but must certify to 150,000 miles, were assigned emission levels further scaled to reflect this added durability. Bin 1 and ZEV vehicles are zero-emissions vehicles. For PM, all vehicles were assigned the full-life standards values. The average grams-per-mile values for all pollutants and for vehicles of each type are shown in Appendix A. For future editions, we will consider whether 50,000-mile standards or full-life standards (120,000 miles) are the better choice for this purpose; see Areas for Future Work, below.

### *Evaporative Emissions from Vehicles*

Evaporative emissions account for a significant portion of the total hydrocarbon inventory (EPA 2009c). Hydrocarbon vapors leak from fuel tanks, lines, and other fuel system components of a vehicle. These evaporative emissions are regulated by EPA and CARB by means of a test wherein stationary vehicles are placed in controlled chambers and subjected to a range of temperatures for a set amount of time. The mass of fuel evaporated is measured, giving results in grams of HC per test. Both federal and California evaporative emissions standards vary by vehicle class, rather than by Tier 2 or LEV II bin (CARB 2009). PZEV vehicles are the exception; they are required to have zero evaporative emissions.

Green Book's treatment of evaporative emissions is in transition. EPA's MOBILE model was used to estimate evaporative emissions in prior Green Book editions. The 2011 Green Book methodology does not use MOBILE, however, and does not account for evaporative emissions. See Areas for Future Work, below.

### *Unregulated In-Use Vehicle Emissions*

Tailpipe emissions of $SO_2$, $N_2O$, $CH_4$, and $CO_2$ are currently not regulated by vehicle, although $SO_2$ emissions are linked to restrictions on fuel sulfur content, and tailpipe standards for $CO_2$, $N_2O$ and $CH_4$ come into effect in model year 2012. $SO_2$ makes a significant contribution to health damages, while $N_2O$, $CH_4$, and $CO_2$ are greenhouse gases. Green Book methodology assumes that these emissions do not depend on a vehicle's Tier 2 / LEV II certification level but are related to the amount and type of fuel consumed.

We use estimates for these emissions from Delucchi (2005) by converting grams-per-mile emissions to a grams-per-gallon value using his assumed average fuel economy (mpg). Estimation details are given in Appendix Table D1.

Greenhouse gas emissions ($N_2O$, $CH_4$, and $CO_2$) from vehicles will be regulated beginning in model year 2012. $N_2O$ and $CH_4$ emissions assigned to vehicles under this year's Green Book methodology are substantially higher than the caps of 0.01 grams per mile $N_2O$ and 0.03 grams per mile ($CH_4$), yet the EPA does not anticipate that gasoline and diesel vehicle will have any difficulty meeting the caps (EPA/DOT 2010). This discrepancy and other issues related to vehicles' greenhouse gas emissions that are raised by the new rule indicate a need to review the treatment of greenhouse gases in future Green Book editions (see Areas for Future Work, below).

### *Fuel Consumption-Based Emissions*

Fuel consumption is the primary determinant of in-use greenhouse gas (GHG) emissions, certain other in-use emissions, and fuel supply-cycle emissions. *Green Book* methodology uses fuel economy data from EPA to evaluate these contributions to a vehicle's environmental impacts.

EPA adopted new methods to estimate fuel economy values for car and light truck labels in 2007 (EPA2006a). According to EPA, these new methods better reflect varying real world driving conditions and bring MPG estimates closer to on-road values. This rule directs car manufacturers to test their vehicles in model year 2008 and beyond using a "five-cycle" test, comprising: the FTP (City) Cycle, the HWFET (Highway) Cycle, the US06 Supplemental FTP Cycle to represent high speed aggressive driving, the SC03 Supplemental FTP Cycle to represent the impact of air conditioner operation at high temperature, and a cold FTP Cycle to reflect the impact of cold temperatures. These five-cycle testing results are then used to calculate adjusted (i.e. label) city and highway fuel economy values. EPA computes a combined fuel economy for label purposes as a harmonic average of the adjusted city and highway values, with 55%/45% weighting of city/highway fuel economy.

*Green Book* adopts EPA's adjusted city and highway results from the 5-cycle testing, which are generally 20 to 30 percent lower than the unadjusted (laboratory) values used to measure manufacturer compliance with Corporate Average Fuel Economy (CAFE) standards. For combined fuel economy, *Green Book* uses a city/highway weighting of 43%/57%, rather than EPA's 55%/45% label weighting. This better captures real-world combined fuel economy, as discussed in the final EPA labeling rule (EPA, 2006a).

For model years 2008 through 2010, EPA allowed the use of an interim calculation method (the "derived 5-cycle" method) to approximate the fuel economy impacts of the additional driving conditions using only the unadjusted city and highway test results:

$$\text{Derived 5-Cycle City FE} = 1/(0.003259 + (1.1805/\text{ unadjusted city})) \qquad (1)$$

$$\text{Derived 5-Cycle Highway FE} = (1/(0.001376+(1.3466/\text{ unadjusted highway})) \qquad (2)$$

For MY 2011, manufacturers are required to calculate fuel economy for select vehicles (known as emission data vehicles) in their fleet using both the 5-cycle and the derived 5-cycle methodology. If there is a significant divergence between the fuel economy estimates produced by the two different methods, then the manufacturer must use full 5-cycle testing for all model types within that test group. If the comparison shows little difference then the manufacturer may continue to report derived 5-cycle data. For these vehicles, *Green Book* uses the derived 5-cycle estimates of city and highway fuel economy. We apply the 43%/57% city/highway split to the derived 5-cycle data to calculate combined fuel economy.

**Plug-in vehicle fuel economy.** EPA data include kWh per mile over the city and highway test cycles for plug-in vehicles. These figures include the losses that occur in vehicle charging (EPA/DOT 2011). Just as for vehicles running on other fuels, however, the test values need to be adjusted to better represent typical driving patterns.

For alternative fuel vehicles, including PHEVs and EVs, manufacturers have the option of using the derived 5-cycle method even after 2010, because not all of the five tests have defined protocols for these vehicles (EPA/DOT 2011). For high fuel economy vehicles, Equations 1 and 2 above yield severe corrections. Converting an EV's kWh per mile values to miles per gallon using the EPA energy conversion of 33,705 kWh per gallon (EPA/DOT 2011) yields fuel economies of well over 100 miles per gallon. A four mile-per-kWh EV, for example, would achieve 135 miles per gallon, resulting in downward corrections of 38 percent and 35 percent for city and highway fuel economies, respectively.

We cap the derived 5-cycle adjustments of Equations 1 and 2 at 30 percent, as was done in the 2011 EPA/DOT fuel economy labeling rule (EPA/DOT 2011). The agencies declined to apply the full correction factor for these vehicles because the data used to generate the derived 5-cycle equations do not include results from any EVs or other high-mpg vehicles, so these corrections are not empirically based. The 30 percent cap on the downward adjustment also has been used by researchers at Argonne National Laboratory (Elgowainy et al. 2010). We note however that plausible arguments have been made against such a cap (ICCT 2010). First, loads not captured over the test cycle (e.g. aerodynamic drag at high speed or initial cooling for air conditioning) are largely independent of a vehicle's fuel economy. Hence the percentage of fuel consumption these loads constitute will grow with increasing fuel economy. Second, with regard to EVs in particular, off-cycle heating loads may in fact be substantially higher for these vehicles, given that engine waste heat will not be available to heat the vehicle. Given the use of the shortfall cap in the Green Book methodology, our treatment of EVs, and to a lesser degree other high efficiency vehicles, may be generous in this regard and should be revisited once data are available.

**Plug-in hybrid vehicles.** We calculate PHEV emissions as the weighted sum of emissions associated with the use of gasoline or diesel and with the use of electricity from the grid, where the weighting corresponds to the percentage of miles driven on each. The percentage of miles the vehicle is operated on electricity is the utility factor (UF) of the vehicle.

For a plug-in hybrid that runs first on electricity alone, then switches to normal hybrid operation once the battery charge is drawn down (an "extended range electric vehicle"), the UF is determined by the vehicle's "all-electric range" (AER), i.e. the distance the vehicle can be driven on electricity. Using data from the 2001 U.S. DOT National Household Travel Survey, the Society of Automotive

Engineers has translated AERs to UFs (SAE 2010). SAE utility factors assume that the vehicle will be charged once a day.

For the 2011 Green Book, the only PHEV on the market was nominally an extended range electric vehicle reported to have an all-electric range of 40 miles. This translates to a UF of 0.62 (SAE 2010), which we used as the weight for electricity in calculating the PHEV's emissions. It should be noted however that SAE has defined more than one type of UF, and a different UF from the one used here may be preferable for Green Book purposes. Furthermore, the approach used to evaluate the extended range EV will need to be refined to accommodate other types of PHEVs entering the market. See Areas for Future Work below for further discussion of these issues.

### *Methodology for Class 2b Trucks*

While Green Book primarily rates light-duty vehicles, i.e. vehicles under 8,500 lbs. GVW, it also includes certain vehicles between 8,500 and 10,000 lbs. GVW (also known as Class 2b trucks). Class 2b SUVs and passenger vans (Medium Duty Passenger Vehicles, or MDPVs) are subject to emissions and, beginning in the 2011 model year, fuel economy standards and labeling requirements. Green Book methodology applies unaltered to these vehicles.

Class 2b pick-up trucks and cargo vans are not subject to the same fuel economy and emissions standards, and the corresponding data is not generally available for these vehicles. Many Class 2b pickups are variants of LDTs and are sold as personal vehicles, however. To include these pick-up trucks in our ratings, we developed a scaling procedure for estimating the vehicles' lifetime average real-world emissions in a manner consistent with vehicles subject to light-duty regulations. For example, if a version of a large, 2wd pickup truck weighs more than 8,500 lb. GVW, fuel economy and emissions certification information data for it will not be available in the EPA database. Therefore, we estimate the fuel economy and emissions of this class 2b vehicle by scaling the estimates for a 2wd (LDT4) version that contains the same engine and can be considered the closest light duty comparison for the heavier 2b truck.

**Fuel economy estimation.** To estimate Class 2b truck fuel economy, we scale from the corresponding LDT vehicle's fuel economy as described below. This scaling is done using mass sensitivity coefficients derived from the An and Ross (1993) fuel economy model. We use coefficients of -0.27 for city fuel economy and -0.23 for highway. Given the small mass differences, a linear approximation is used; in the city cycle case, for example:

$$MPG_2 = MPG_1\,[1 - (0.27)\,(m_2 - m_1)/m_1]$$

where "m" designates mass (vehicle curb weight), mpg is fuel economy, and subscripts refer to the base LDT for which fuel economy is known (1) and the Class 2b variant for which fuel economy needs to be estimated (2). These coefficients assume that other key vehicle parameters are constant; in particular, engine displacement is constant because we address only Class 2b trucks matched by engine and transmission type to a given LDT. Parameters that would also affect fuel economy, but for which we did not adjust, include gear ratios, the n/v (rpm per mph) ratio, and driveline friction, among others. For example, higher n/v and higher driveline friction in a Class 2b variant would push its actual fuel economy lower than what we estimate; however, these data were not readily available. Fuel economy data for all Class 2b pickup trucks and cargo vans will likely be available no later than the 2014 model year, when the new GHG/fuel efficiency standards program for vehicles begins.

**Emissions estimation.** As for all other vehicles, the in-use criteria pollutant component of an MDPV's damage cost (EDX) is based directly on the emissions standards to which it is certified. This year, six out of the eight Class 2b pickups that we scored had been voluntarily certified to federal Tier 2 emission standards. Vehicles that don't have a tailpipe emission certification are scored according to their California LEV II certification.

## Upstream Emissions

Pollution results from activities throughout the fuel supply cycle, from the wellhead to the fuel pump for gasoline or from the coal mine to the wall plug for electricity, for example.

### *Gasoline, Diesel and CNG Vehicles*

Delucchi (2005) models fuel supply cycle emissions of CO, HC, $NO_x$, $PM_{10}$, $SO_2$, $CH_4$, $N_2O$ and $CO_2$ for various fuels, including gasoline, diesel, and CNG. His results are expressed in grams per million British thermal units (grams per $10^6$ Btu), and those relevant to our analysis are detailed in Appendix Table D2. We use these figures together with each vehicle's in-use fuel economy to compute grams per mile estimates for these emissions. HC emissions associated with refueling are included as part of these fuel supply cycle emissions, but those that occur once fuel is in a vehicle are included under "Evaporative Emissions," above.

### *Electric and Plug-In Hybrid-Electric Vehicles*

All emissions associated with the use of an electric vehicle (EV) fall in the fuel supply cycle category. Grams per mile emissions from a vehicle running on electricity generated off-board are calculated as the product of the vehicle's average kilowatt hours (kWh) per mile and a set of grams per kWh emission factors for power generation. Kilowatt hour per mile data for these vehicles is discussed in the "Plug-in vehicle fuel economy" section above. To calculate grams emitted per kWh, we use EIA data for the national average power generation mix in 2009 (EIA 2010), as detailed in Appendix Table D3. These figures reflect distribution losses. Our valuation assumptions for health effects treat power plant emissions differently than vehicle emissions due to differences in exposed population, as discussed below. Our methodology does not reflect geographic or temporal differences in electricity generation mix, however, which can result in substantial variations in an EV's environmental impacts, depending on where and when it is charged.

## Vehicle Life-Cycle Emissions

The calculation of vehicle life-cycle GHG and criteria pollutant emissions in the Green Book methodology reflects manufacturing, assembly, and recycling/disposal. This year, we used Argonne National Laboratory's GREET 2.7 model as the basis for the analysis. GREET 2.7 breaks vehicle life cycle impacts down into four categories to estimate GHG and criteria pollutant emissions: vehicle components, batteries, fluids and vehicle assembly, disposal and recycling (ADR). The model includes recycling and disposal impacts and permits the incorporation of details on key components, such as batteries, that differentiate the vehicle cycle impacts of more advanced vehicles from those of conventional vehicles. GREET 2.7 provides emissions and energy estimates for internal combustion engine (ICE), hybrid-electric, and fuel cell cars and SUVs. Results for pickup trucks are forthcoming (Burnham 2010).

GREET calculates vehicle life-cycle energy and emissions based on a large number of vehicle-specific inputs (ANL 2006). As most of these inputs are not available on a model-by-model basis, we use GREET default values for most, varying only vehicle weight and class in the case of an ICE vehicle. This approach results in emission estimates for four key pollutants (among others): carbon monoxide, nitrogen oxide, hydrocarbons, and particulate matter. The values we generated from GREET showed the emissions estimates for each pollutant and vehicle class to be linear in vehicle weight.

The y-intercepts of some of the linear formulae generated in this way are quite large, indicating that large quantities of certain pollutants associated with the vehicle life-cycle are independent of vehicle weight. This is partly due to the fact that GREET does not automatically scale the weights of a vehicle's battery, tires, and fluids or its assembly, disposal and recycling emissions with vehicle weight. However, the weights of tires, batteries and fluids in reality would tend to increase with the weight of the vehicle. For some pollutants, over half of the emissions from assembly, disposal and recycling (ADR) is associated with the assembly process, which may in fact be largely independent of vehicle weight. Disposal and recycling, on the other hand, could be expected to be roughly proportional to vehicle weight.

In light of these various considerations, we adjusted the linear formulae generated using GREET 2.7 by fixing their values at the default vehicle weight while cutting the y-intercepts in half to better reflect the proportion of emissions that should scale by weight. The slopes and intercepts defining the resultant linear relationships for conventional vehicles are shown in Appendix Table B1. The intercept adjustments warrant further consideration; see Areas for Future Work below.

For hybrid-electric vehicles, we input the size and composition of the battery along with vehicle weight to GREET 2.7. This year's hybrid offerings include vehicles with nickel metal hydride (Ni-MH) and vehicles with lithium-ion (Li-ion) composition. GREET assumes that Ni-MH batteries are replaced once during a vehicle's life, but that Li-ion batteries last for the life of the vehicle (ANL 2006). We adopt this assumption for the 2011 Green Book but will reconsider it for future editions. This approach, and reducing the intercepts as described above for conventional ICE vehicles, we developed formulae for hybrid car and truck emissions as linear functions of vehicle weight and battery weight.

For all-electric vehicles, we used GREET's existing fuel cell vehicle methodology, since the model does not yet contain any electric-vehicle-specific calculations. Based on discussions with Argonne National Laboratory, we represent an electric vehicle as a fuel cell vehicle in GREET 2.7 by increasing the battery weight input and removing the fuel stack and auxiliaries (fuel storage tank, piping, etc.) altogether (Burnham 2010). Plug-in electric and all-electric vehicles in 2011 had lithium-ion batteries.

Appendix Tables B2 and B3 describe the resultant relationships for hybrids and plug-in vehicles.

## IMPACT VALUATION AND RESULTS

For characterizing the environmental damage of various emissions over the vehicle life cycle, we adopt an approach based on environmental economics. Our environmental damage index weights the relative impacts of the pollutants using factors derived from damage cost estimates. It also involves a non-economic judgment that assigns a monetary value to greenhouse gases relative to the economically derived values for conventionally regulated pollutants.

In economic terms, most environmental impacts are considered externalities, that is, effects on others that are not accounted for in market transactions by the parties causing the effects. Delucchi & McCubbin (2010) identifies a significant range in the value of human health externalities of air pollution from U.S. motor vehicle use. Estimates vary from \$5-\$75 billion per year (2006\$), reflecting the uncertainty inherent in such estimates. These estimates correspond to a per-vehicle external cost of \$21-295 per year. By way of comparison, estimates from the 2011 run of Green Book indicate that annual external costs range from \$158-478 for the range of vehicles offered this year.

### Environmental Damage Costs

Among the common approaches for estimating environmental externalities are use of control costs and use of damage costs. Control costs are based on observations of the costs incurred to reduce pollution such as the cost of clean-up devices. Damage costs are based on observations of the harm caused by pollution, derived, for example, from epidemiological studies. We use damage costs, which avoid incorrect valuation due to: (1) market, regulatory, and implementation imperfections that lead to control costs being different than damage costs; and (2) the fact that existing pollution controls already internalize some of the costs. Examples of such internalization are the higher cost of a car due to its emissions control system and the higher cost of gasoline due to reformulation requirements.

The harm caused by air pollution depends on where it is emitted relative to exposed populations and other subjects of concern. Transported pollutants are subject to dilution and transformation. The impact of, say, one gram of PM emitted from a vehicle tailpipe differs substantially from the impact of one gram of PM emitted from a power plant. Thus, a single damage cost value should not be used for a given pollutant independently of where it is emitted. Delucchi and McCubbin (1996) examined this issue in some depth for the major pollutants associated with motor vehicles and their supporting infrastructures (including manufacturing plants, petroleum refineries, electric utilities, etc.). They simulated the fraction of a pollutant emitted from a given source that would reach exposed subjects in various locations. Their simulation results were normalized relative to exposures to light-duty vehicle PM emissions, yielding what might be called damage cost reduction factors. Reviewing the wide range of resulting factors, we selected a factor of ten for reducing the damage cost of pollutants from electric utilities relative to those from vehicles. We selected a reduction factor of five for factories and refineries, which entail relatively higher worker and community exposures.

For base damage costs—those representing the impacts of pollutants directly emitted from motor vehicles—we adopted the geometric means of the low and high health cost estimates of Delucchi (2004, Table 1-A1). The resulting estimates for major pollutants by location are shown in Table 3. These estimates place a relatively high value on reduction of fine PM and its precursors (particularly $SO_2$ and $NO_x$). In contrast, earlier estimates (e.g., as in the review by Wang and Santini 1995) emphasized reduction of ozone and its precursors, resulting in a relatively high value for avoided HC emissions, as well as for $NO_x$. California's smog index (CARB 1996) matches the type of valuation implied, for example, by Wang and Santini (1995) estimates, in which the damage cost ($/kg) of HC is about 50% of that of $NO_x$. By contrast, the damage cost of HC is only 8% of that of $NO_x$ for the Delucchi (2004) estimates that we adopt here. Thus, our valuations reflect a significant benefit for Tier 2 and LEV II standards, which, depending on bin (or the specific LEV II standard), can cut nominal $NO_x$ emissions by a factor of eight or more.

**Table 2. Damage Cost Estimates for Principal Air Pollutants**

| **Pollutant** | **Marginal Cost by Location of Emissions (2004$/kg)** | | |
|---|---|---|---|
| | Motor Vehicles [a] | Refineries and Factories [b] | Electric Power Plants [c] |
| CO | 0.04 | 0.008 | 0.004 |
| HC or VOC | 0.47 | 0.094 | 0.047 |
| $NO_X$ | 6.24 | 1.25 | 0.62 |
| $SO_2$ | 29.42 | 5.88 | 2.94 |
| $PM_{10}$ | 50.09 | 10.02 | 5.01 |

Notes:

a. Geometric mean of low and high health cost estimates from Delucchi (2004), Table 1-A1.
b. Values for motor vehicles (a) reduced by a factor of 5.
c. Values for motor vehicles (a) reduced by a factor of 10.

Since the average U.S. electricity generation mix includes a significant share (20%) of nuclear power, it is necessary to include the environmental damage associated with the nuclear fuel cycle. Its environmental impacts fall largely outside of the criteria air pollutant and GHG impacts on which we base our damage cost estimates for fossil fuels and their products. External costs of nuclear power have been extensively investigated for electric sector studies. Population exposures to radiation occur during uranium extraction and processing to produce nuclear fuel, during normal reactor functioning, and during radioactive waste disposal and plant decommissioning. Many of these latter impacts are highly uncertain because these end-phases of the nuclear fuel cycle are far from fully addressed. The most problematic cost is that associated with accidents, which can be disastrous, but are rare and unpredictable and so are very poorly amenable to statistical characterization.

Ottinger (1991) provides summary external cost estimates of 0.11¢/kWh for routine operations, 0.50¢/kWh for decommissioning, and 2.3¢/kWh for accidents. The accident portion is based largely on allocating the damage estimates associated with the Chernobyl disaster over the operating history base of nuclear power. (Impacts of the worst U.S. accident, at Three Mile Island, are nearly negligible in comparison to Chernobyl.) Given the relatively safe history of U.S. nuclear operations, and the high uncertainty associated with accident estimates, we use only the two non-accident costs, implying an external cost of 0.61¢/kWh for nuclear power as part of the U.S. average electricity generation mix. This issue will likely be extensively reviewed in the wake of the earthquake-induced nuclear disaster at Japan's Fukushima Daiichi nuclear plant in 2011.

As shown in Appendix Table D3, prorating this estimate by the 20.1% share of nuclear power in the mix adds 0.17¢/kWh (about 20%) to the overall external cost of electricity, which we estimate at 0.82¢/kWh. This value is used to calculate the environmental damage from electric vehicle use and electricity used in vehicle manufacturing.

Given the global nature of the problem, the fact that their impacts will grow in the future, and the lack of retrospective impacts assessments (in contrasts to several decades of epidemiologic and other work available for traditional air pollutants), assigning a meaningful damage cost to GHG emissions is very difficult. Published estimates vary greatly in magnitude. For example, the analysis of impacts of the 2012-2016 fuel economy and GHG emissions rule considered values ranging from $5 to $65 per metric ton of $CO_2$ (2007 dollars) as the social cost of carbon (EPA/DOT 2010).

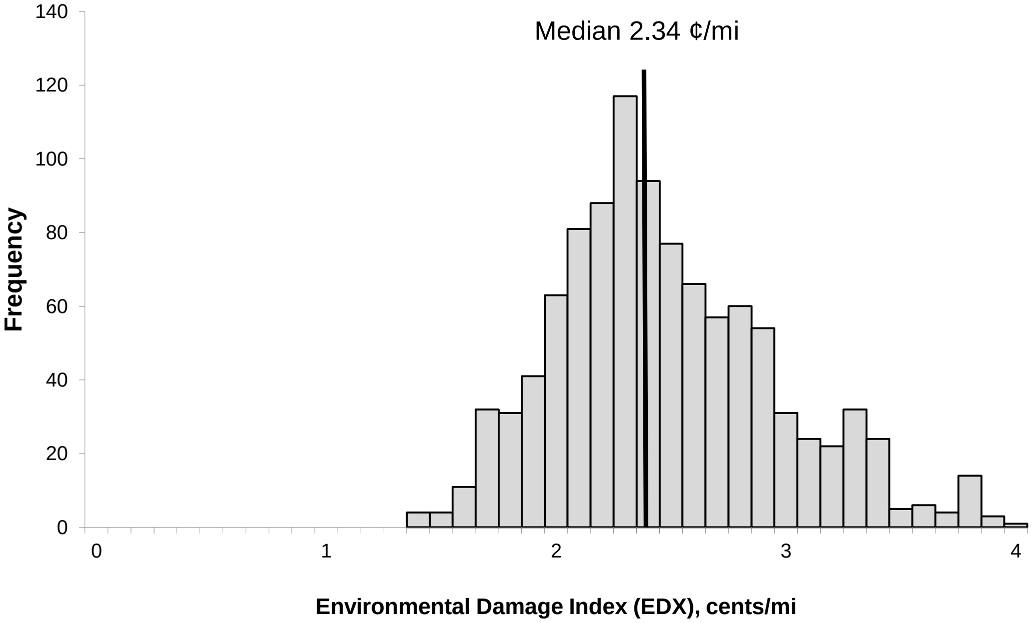
In light of difficulty of assigning a damage cost to GHG emissions, the original Green Book methodology treated GHG emissions as equally important as criteria air pollutants in determining the rating of an average vehicle (DeCicco & Thomas 1999). To implement this assumption, a cost for $CO_2$-equivalent GHG emissions was calculated so that, for an average vehicle, one-half of the EDX would be GHG-related and the other half would be equal to the sum of the health damage costs from other pollutants (the total estimated health effects of PM, $NO_x$, VOC, etc.). This established a quasi-damage cost for GHG of $87 per ton of carbon (2004 dollars), or $27 per ton $CO_2$-equivalent, which we have kept constant (in real dollars) since that time. Comparing once again with the treatment of GHG damage costs in MY2012-2016 fuel economy and GHG rulemaking, the agencies selected $21 per metric ton $CO_2$ (2007 dollars), or $17.35 per short ton $CO_2$ (2004 dollars), as the primary impact cost for their analyses (EPA/DOT 2010). Thus the Green Book damage cost is larger than, but of the same order as, estimates in the current literature.

## Summary of Life Cycle Estimates

We compiled a database of all new light-duty vehicles on the U.S. market in 2011 and carried out the rating analysis for each configuration of every make and model (1,048 in all). Figure 1 shows the resulting EDX distribution: (a) for the overall light-duty fleet and (b) separately for cars and light trucks. These results are not sales-weighted and so represent the "menu" of vehicles offered to the market, as opposed to market outcome. The 2011 EDX results range from 1.32¢/mi (a PZEV-certified compressed natural gas compact car) to 3.98¢/mi (a 16-cylinder, 4-wheel drive European sports car). The median is 2.34¢/mi and one-half of the models fall between 2.10 and 2.72¢/mi.

## Figure 1. Distribution of Environmental Damage Index for Model Year 2011

### (a) Cars and Light Trucks Combined



### (b) Cars and Light Trucks Shown Separately

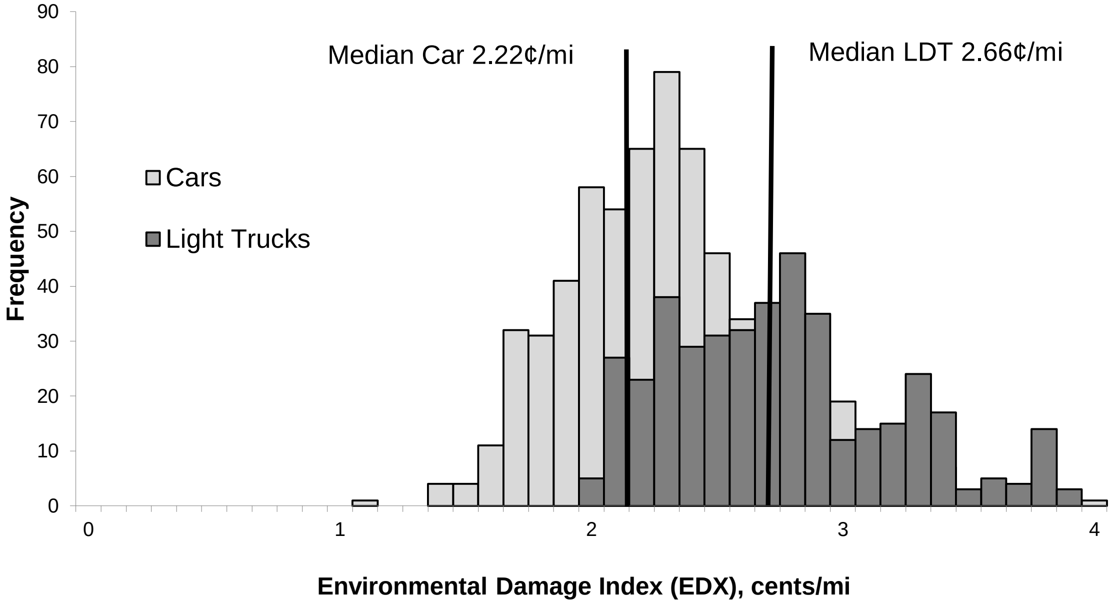


Figure 1 illustrates how U.S. vehicles fall into two major classes: passenger cars (coupes, sedans, and station wagons) and light trucks (pickups, minivans, and sport utilities).1 The gap in the distribution of cars versus light trucks narrows this year due to the use of emission standards in the

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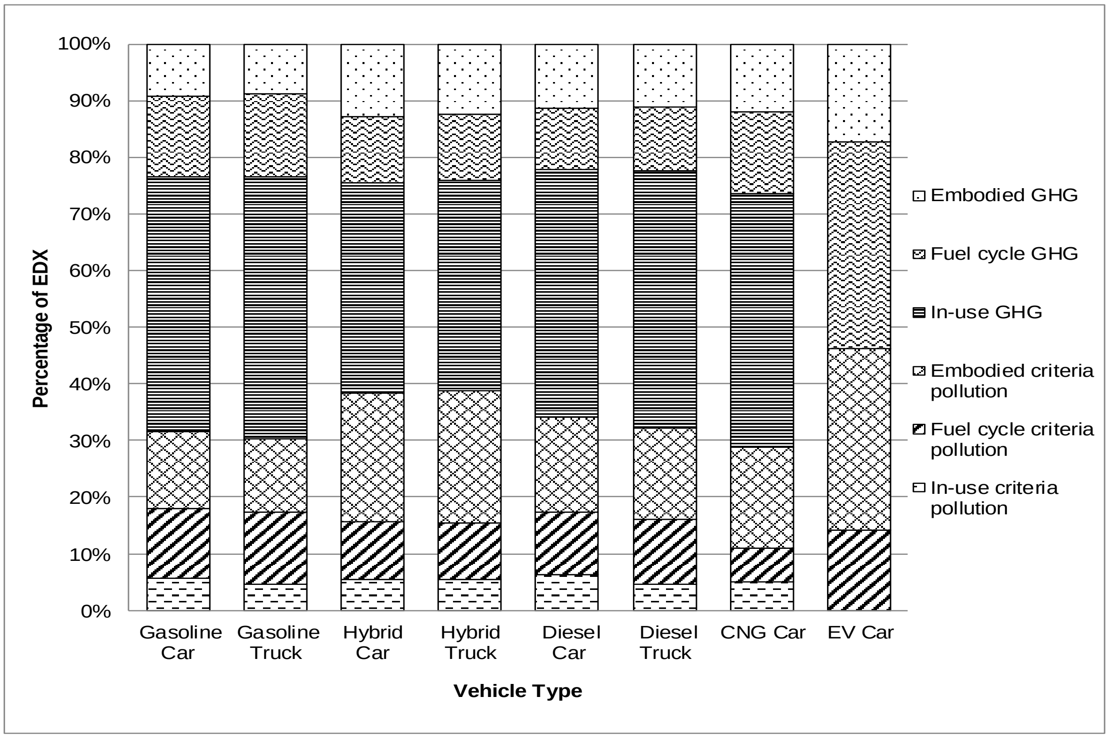
[1] Green Book classification does not reflect the shift of 2-wheel drive SUVs under 6000 lbs. GVWR from the truck class to the car class for purposes of fuel economy standards, starting with model year 2011.

rating of vehicles. The median EDX for passenger cars is 2.22¢/mi, while the median for light-duty trucks is 2.66¢/mi. Most light trucks fall into the LDT2 category. This model year, the majority of LDT2 vehicle configurations are jointly certified to California ULEV II and federal Tier 2 bin 5, the same standard to which the majority of passenger cars are certified.

Appendix Tables C1 and C2 detail the EDX calculations for an average model year 2011 car and light truck, respectively. The first three parts of the table itemize health-related criteria emissions impacts for: (a) direct vehicle emissions; (b) upstream emissions; and (c) emissions embodied in materials and vehicle assembly and disposal. Lifetime average (g/mi) emissions rates are multiplied by damage costs from Table 2 to obtain life cycle cost estimates in cents per mile. For the average car, the three criteria emissions components are 0.11¢/mi (6% of total EDX) at the vehicle (in use), 0.24¢/mi (12%) from the fuel supply cycle, and 0.27¢/mi (14%) embodied, summing to 0.63¢/mi (100% of life cycle criteria emissions impact as calculated here). The criteria emissions components for the average 2011 light truck are similarly distributed (5% at the vehicle, 13% from the fuel cycle, and 13% embodied), albeit with a sum total of 0.79¢/mi—25% higher than the criteria emissions total of the average 2011 car.

Greenhouse gas emissions calculations are shown in Tables C1(d) and C2(d). Emissions from each source, drawn from parts (a)–(c) of the table, are summed and then multiplied by the global warming potential (GWP) that represents the radiative forcing of each GHG species compared to that of $CO_2$ (Delucchi 2005). The total lifetime average $CO_2$-equivalent emission rate (e.g., 575 g/mi for the average car) is then multiplied by the quasi-damage cost chosen for GHG emissions. In the first edition of Green Book, in 1998, the GHG impact and health-related (criteria emissions) impact were the same by definition for the average LDV at the time, reflecting ACEEE's judgment at that time that GHG emissions and criteria emissions should have equal weight in determining the average vehicle's EDX. We have maintained the MY1998 damage cost factor for GHG emissions. With the decline in vehicles' emissions of criteria pollutants and our use of nominal emissions standard values rather than estimated in-use emissions, the percentage of a vehicle's EDX attributable to GHGs has risen. GHGs accounted for approximately 69% of an average vehicle's EDX in MY2011.

**Figure 2. EDX Breakdown by Vehicle Technology**



With this assumed GHG damage cost, the three GHG emissions components for the average car are 0.90¢/mi (45% of total of total EDX) at the vehicle, 0.28¢/mi (14%) from the fuel supply cycle, and 0.18¢/mi (9%) embodied, summing to 1.36¢/mi (100% of GHG emissions impact as calculated here). The GHG components for the average 2011 light truck are similarly distributed: 46% at the vehicle, 15% from the fuel cycle, and 8% embodied), summing to a total of 1.83¢/mi. The criteria- and GHG-related calculations are summarized in Appendix Tables C1 and C2, with resulting total EDXs of 1.99¢/mi and 2.61¢/mi, respectively. Figure 2 shows how the components of the EDX vary with vehicle technology and fuel.

## Public Presentation of Results

Representing a vehicle's environmental damage as a lifetime average external cost per mile, the EDX is an abstraction that may be difficult for many consumers to appreciate. Therefore, to facilitate communication and make it easier to compare vehicles, we derived from the EDX two indicators to convey rankings in ACEEE's Green Book®. One is a Green Score on a higher-is-better scale of 0 to 100. The other is a set of class ranking symbols that compare vehicles within a given size class.

The Green Score allows comparisons both within and across classes. It is not tied to a particular model year, so it can accommodate updates to the methodology while maintaining a consistent scale for consumers. It also leaves room to reflect future improvements in vehicle environmental performance. To map the EDX from a [0,∞] range inversely to the Green Score on a [0,100] range, we use a gamma function to spread out the scores for future "green" vehicles at the expense of less differentiation among current vehicles. Presently, in fact, the variability in EDX within vehicle classes is relatively small. The mapping, shown in Figure 3, is:

$$\text{Green Score} = a \cdot \frac{e^{-\mathrm{EDX}/c}}{(1 + \mathrm{EDX}/c)^{b}}$$

with a = 100, b = 3 and c = 8.19¢/mi. A perfect score of 100 is unattainable since it would require an EDX of 0. Using the parameters shown, model year 2011 Green Scores range from 19 to 54, with an overall average of 35.

When car shopping, many consumers target a given vehicle class and are unlikely, for example, to consider a subcompact when looking for a minivan. To facilitate comparisons within classes, we developed the five-tier class ranking scheme shown in Table 3. In assigning class rankings, we considered the number of vehicles in each class and natural breaks in the distribution rather than rigidly applying the cutpoints listed in the table. An additional constraint was that no vehicles that scored worse than the model year average (a Green Score of 35, corresponding to an EDX of 2.42¢/mi) could obtain the Superior ranking. Details of the EDX distributions and exact cutpoints used for each class are provided in Appendix E.

**Figure 3. Green Score vs. Environmental Damage Index (EDX), with Sample Vehicles**

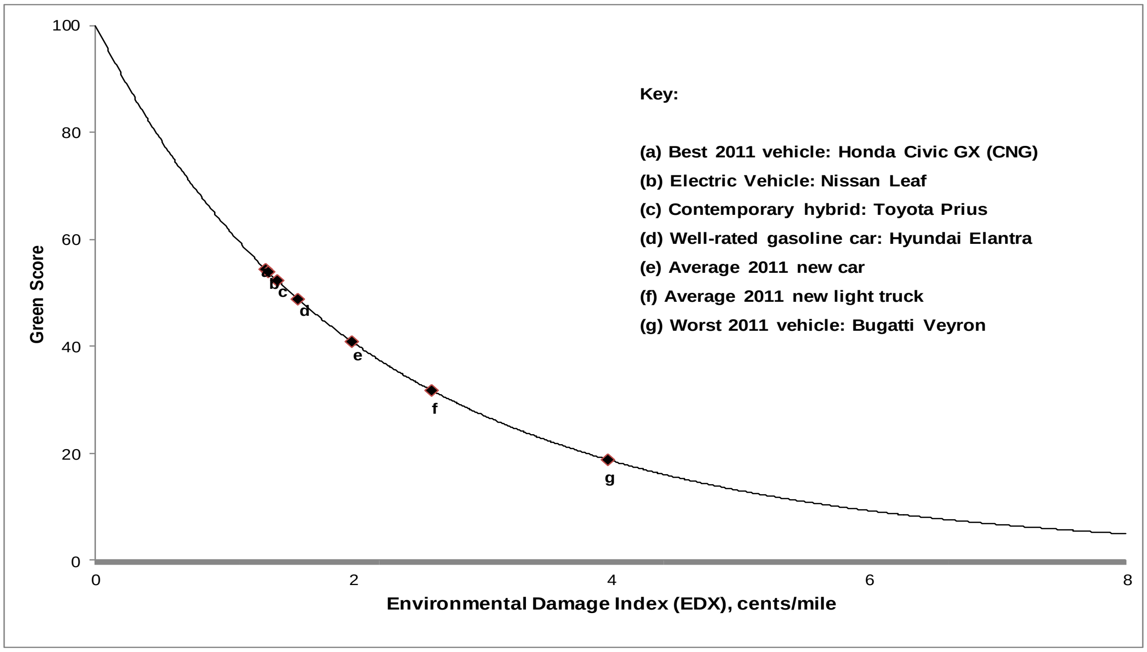


**Table 3. Percentile Guidelines and Symbols for Within-Class Vehicle Rankings**

| Percentile Guidelines | Class Ranking |
|---|---|
| 95% + | Superior [a] |
| 80–95% | Above Average |
| 35–80% | Average |
| 15–35% | Below Average |
| 0–15% | Inferior |

Notes:

a. For a Superior ranking, a vehicle must also have a Green Score of no less than 35, corresponding to the MY2011 combined car-truck average EDX of 2.42¢/mi.

# AREAS FOR FUTURE WORK

This methodology provides a flexible framework that can be refined and updated as new data become available. The parameters and assumptions described in this document reflect updates made since the 2004 methodology report (Kliesch 2004). Appendix F summarizes the methodological updates since that time. Several areas for improvement are highlighted below and the authors look forward to receiving comments regarding other methodological issues to address

## Use of Emissions Standards Values to Represent Average Lifetime Vehicle Emissions; Lifetime Miles

The use of emissions standards values to represent average per-mile emissions over the life of a vehicle, adopted for the 2011 Green Book, reflects a shortage of up-to-date data on in-use emissions, and how they may vary by vehicle type, rather than confidence that today's vehicles in real-world operation will adhere to emissions levels to which they are certified. We will continue to monitor research and data collection on emissions of Tier 2 vehicles to determine whether the current approach can be improved.

For the 2011 Green Book, we used 50,000-mile standards to represent average lifetime emissions for $NO_x$, NMOG, and CO. Given that cars today are driven an average of about 150,000 miles and trucks 180,000 miles over their lifetimes (DOT 2006), "full useful life" standards (120,000 miles), or the average of 50,000-mile and 120,000-mile standards may be a better default value for average lifetime emissions. The full-life standards are 20 to 40 percent higher than the 50,000-mile standards, so using them to estimate lifetime emissions would increase the role of in-use criteria emissions in the EDX of most vehicles, though only modestly.

## Evaporative Emissions

The 2011 Green Book methodology does not account for evaporative emissions, which are a significant source of hydrocarbon emissions. Federal and California standards for evaporative emissions differ by vehicle class. Also, diesel and CNG vehicles, in contrast to non-PZEV gasoline vehicles, have very low evaporative emissions. For gasoline vehicles, increased ethanol content in low-ethanol blends is raising new questions about evaporative emissions. In light of these considerations, we plan to reintroduce evaporative emissions into the scoring in future editions.

## In-Use Greenhouse Gas Emissions

With the advent of greenhouse gas standards for light-duty vehicles in 2012, several issues relating to these emissions call for reexamination for Green Book purposes. As discussed above, we base our estimates of in-use $N_2O$ and $CH_4$ on Delucchi (2005), which assigned emissions of 0.057 g/mi and 0.043 g/mi, respectively for these two pollutants. These rates are much higher than the caps of 0.010 g/mi and 0.03 g/mi, respectively, in the 2012-2016 greenhouse gas rule, yet EPA estimates that these caps are approximately twice what an average vehicle emits per mile today, and intends the standard as a safeguard against future increases (EPA/DOT 2010). Moreover, EPA believes that CNG vehicles should be capable of meeting the $CH_4$ cap, while Green Book estimates CNG vehicles' emissions of $CH_4$ to be an order of magnitude higher. These differences call for a new look at the treatment of in-use emissions of $N_2O$ and $CH_4$ in Green Book.

The new rule raises additional issues related to vehicles' greenhouse gas emissions that Green Book methodology does not currently reflect. These include emissions due to the air conditioning system, including leakage of refrigerant and emissions during disposal. Also, the EPA notes that emissions of both $CH_4$ and $N_2O$ can depend on emissions control technology, and hence cannot be estimated solely as functions of fuel throughput as Green Book methodology currently assumes. Finally, the agencies use $CO_2$ gram per gallon conversions of 8,887 g/gallon of gasoline and 10,180 g/gallon of diesel in the rule. Green Book currently uses 8,558 grams per gallon gasoline and 9,936 grams per gallon diesel per DeLucchi (2005), as shown in Appendix Table D1, to estimate vehicle in-use emissions. Thus several issues related to greenhouse gas emissions from vehicles warrant further investigation.

## Plug-In Hybrid Fuel Economy

In evaluating the one available plug-in hybrid in MY2011, we used a "fleet" utility factor, as defined by SAE (SAE 2010). The fleet utility factor for a distance D is the percentage of miles traveled in the U.S. that are among the first D miles of the day driven by some vehicle. In the 2011 vehicle labeling rule (EPA/DOT 2011), EPA and DOT noted that, while fleet utility factors are appropriate for estimating national fuel and emissions benefits of plug-in hybrid deployment, the "multiday individual" utility factors defined by SAE will better capture these vehicles' benefits to an average user. We will consider using individual UFs in future Green Book editions.

Another issue to be resolved is that the applicability of the concept of all-electric range, and the associated utility factor, is limited. PHEVs in general will often run in "blended mode", in which both grid electricity and gasoline or diesel power the vehicle, rather than running in all-electric mode until the battery is depleted. Methods for calculating PHEV fuel economy and emissions are still under development. The labeling rule adopted in May 2011 by EPA and NHTSA prescribes a complex approach to generating fuel economy numbers based on energy consumption over multiple city and highway cycle tests, repeated until the battery is depleted. More work is required to determine how these results could be summarized and made available for each PHEV model in such a form as to allow calculation of average per-mile city and highway consumption of electricity and petroleum fuels, and hence emissions, for purposes of Green Book ratings.

## Compressed Natural Gas (CNG) Vehicles

Estimates of upstream emissions from fuel production, distribution and vehicle refueling from the Lifecycle Emissions Model (LEM) (DeLucchi 2005), which are used in Green Book methodology, differ substantially from estimates in GREET 1.8, Argonne National Lab's fuel-cycle vehicle model. GREET's estimates of carbon monoxide (CO) and nitrogen oxides ($NO_x$) emissions are significantly lower for CNG vehicles than the LEM (DeLucchi 2005). Likewise, estimates of methane ($CH_4$), hydrocarbons, nitrous oxides ($N_2O$) are lower but not vastly different than those used in the current Green Book methodology. On the other hand, particulate matter (PM10), carbon dioxide ($CO_2$) and sulfur oxides ($SO_x$) emissions are markedly higher using GREET 1.8 results. The impact of using these figures to score the sole CNG vehicle on the market is minimal, however, yielding a 2% increase in the EDX. Nonetheless, further investigation of these discrepancies is warranted.

Accurately representing life-cycle impacts of CNG vehicles is an ongoing effort. Recent debate surrounding the increased use of the hydraulic fracturing (or fracking) method to extract natural gas suggests that water contamination impacts would be an important addition to a life cycle analysis like the Green Book's. With the exception of certain nuclear power impacts, Green Book methodology to date has considered only air pollution emissions, but concerns not only with natural gas extraction but also with oil spills and coal mining raise the question of whether a more comprehensive approach is feasible.

We will continue to investigate the possibility of using more recent and comprehensive emissions estimates for CNG vehicles.

## Vehicle Life-Cycle Emissions

Comments from reviewers included reservations about our application of GREET 2.7, one of the major updates to the methodology. GREET was developed to compare the environmental impacts of hypothetical vehicles based on their fuel, technologies, etc., not to compare real vehicles models. In choosing two parameters, vehicle weight and battery weight, to compare vehicles within each class, we could be overstating the importance of these two parameters and/or overlooking other important determinants of emissions levels.

Vehicle weight alone has been the proxy for emissions from the vehicle life-cycle in Green Book methodology to date, and we continue to believe this is the single most important parameter in determining the environmental impact of the vehicle life cycle. We added battery weight to the factors to be considered (so that a pound of battery weight is treated differently from a pound of generic vehicle weight) to start addressing concerns that the production of materials used in batteries, as well as the battery assembly, recycling and disposal processes, could have substantial environmental impacts that offset the environmental benefits of hybrid and plug-in vehicles. This year's results show that accounting for such impacts may reorder the very top vehicles in our ratings but that large-battery vehicles nonetheless will tend to score very well due to their high efficiency of operation (see Appendix F).

How robust this approach is, especially given the variations in sourcing and processing of many materials, remains unclear, and we will investigate further the question of whether singling out batteries for special treatment is warranted. It is worth noting, however, that the primary difference between battery and vehicle per-pound impacts relates to assembly, rather than production of materials. Emissions associated with materials production for batteries are about twice those of vehicle materials production on a per-pound basis. Assembly accounts for 42 to 56 percent of NiMH and Li-ion battery emissions according to GREET, and battery assembly emissions are generally an order of magnitude higher per pound than are emissions from vehicle assembly. While the assembly energy use may lend itself to a more uniform and objective analysis than materials production, GREET authors note: "The large discrepancy between the [assembly energy] values for Ni-MH batteries is troubling, and even the other values have been questioned because the energy required for vehicle assembly is much lower" (ANL 2006). Hence this remains an important topic to revisit for subsequent Green Book editions.

We also note here that, at a minimum, the adjustments we made to the linear formulae generated through GREET 2.7 for emissions as functions of vehicle and battery weight need further attention. The 2011 Green Book methodology intercepts of these functions by half across the board. A pollutant-by-pollutant approach that considers the contributions of each vehicle life-cycle component to the intercept value would be more appropriate, however.

## Battery Replacement for Hybrid-Electric Vehicles

In 2011, hybrid-electric vehicles with nickel metal hydride batteries (Ni-MH) incorporate the GREET 2.7 default assumption that these batteries are replaced once during a vehicle's lifetime. Reviewers questioned this assumption. We are not aware of data on the replacement rate for Ni-MH hybrid batteries, but anecdotal evidence indicates that only a small fraction of hybrid owners have required battery replacements since the purchase of their vehicles. We evaluated the impact of assuming no battery replacements for Ni-MH batteries and found that Green Scores for hybrid vehicles increased by 0 to 2 points. We will revisit the replacement assumption for the next Green Book edit.

## Environmental Damage Costs

The damage costs used in our life-cycle analysis of model year 2011 vehicles were obtained from DeLucchi (2004). The Office of Management and Budget (OMB) published estimates of health externality impacts more recently (OMB 2005) which are outlined in Table 4 below. We will evaluate whether to include these official estimates in future cycles of Green Book.

**Table 4. Damage Costs of Motor Vehicles**

| **Pollutant** | **Marginal Damage Cost** (2004$/kg) | | |
|---|---|---|---|
| | Current ACEEE Green Book | OMB (min) [a] | OMB (max) [a] |
| CO | 0.04 | | |
| HC or VOC | 0.47 | 0.64 | 2.88 |
| $NO_X$ | 6.24 | 1.17 | 12.37 |
| $SO_2$ | 29.42 | 1.81 | 19.20 |
| $PM_{10}$ | 50.09 | 10.67 | 106.66 |

Notes:

a. Original values provided in 2001 dollars. Converted to 2004 dollars using the ratio of CPI values between 2001 and 2004.

We will also review our assumptions regarding the urban/rural breakdown of emissions, which are used to determine the damage costs for pollution from refineries and factories and electric power plants. Following the suggestion of a reviewer, we will also consider whether a similar distinction should be made in determining damage costs for tailpipe emissions.

### Other Areas for Future Work

**Electricity Generation Factors** Emissions associated with plug-in vehicle use were calculated using EIA electricity generation data for 2009. To better reflect emissions over the life of a plug-in, we will review electricity generation projections and consider calculating plug-in emissions based on those projections.

**2-Wheel Drive SUV Classification** For model years 2011 and beyond, DOT has reclassified 2-wheel drive SUVs with gross vehicle weight rating up to 6000 pounds as cars for fuel economy purposes (DOT 2009). This moves many “crossover” vehicles from the truck category to the car category. We will consider adopting this change in vehicle classification for *Green Book* purposes. This would not affect vehicles’ green scores, but could alter the Greener Choices list, for example.

**PM2.5** Fine particles are generally a greater threat to health than coarser particles are. *Green Book*’s current treatment of particulate matter focuses on $PM_{10}$, because vehicles are regulated for $PM_{10}$ emissions. Other information such as GREET outputs is reported separately for $PM_{2.5}$, however. We will investigate the available information on vehicles’ $PM_{2.5}$ emissions as a fraction of $PM_{10}$ emissions for each fuel and consider supplementing or replacing $PM_{10}$ emissions by $PM_{2.5}$ emissions (and health damage costs) in the calculation of EDX.

## CONCLUSION

Developing and refining ACEEE’s Green Book®: The Environmental Guide to Cars and Trucks involves exploring many issues related to the life cycle environmental impacts of vehicles and how they can be communicated to consumers. Our ratings can help foster a market for vehicle designs and technologies with reduced environmental burdens, which will be crucial for progress toward an environmentally sustainable transportation system. We welcome suggestions for improving Green Book in terms of both methodology and presentation.

# REFERENCES

An, F. and M. Ross. 1993. *A Model of Fuel Economy and Driving Patterns*. SAE Paper 930328. Warrendale, PA: Society of Automotive Engineers.

ANL. 2006. *Development and Applications of GREET 2.7 – The Transportation Vehicle Cycle Model.* Argonne, IL:, Argonne National Laboratory.

Burnham, A. 2010. Personal Communication with Shruti Vaidyanathan. Argonne, IL: Argonne National Laboratory, November

Calvert, J.G., J.B. Heywood, R.F. Sawyer, and J.H. Seinfeld. 1993. *Achieving Acceptable Air Quality: Some Reflections on Controlling Vehicle Emissions*. Science 261: 37-45, July 2.

CARB. 1996. *California Motor Vehicle Emission Control and Smog Index Label Specifications*. Sacramento, CA: California Air Resource Board.

———. 2009. *California Evaporative Emissions Standards and Test Procedures for 2001 and Subsequent Model Motor Vehicles.* http://www.arb.ca.gov/regact/2008/phev09/evaptp.pdf. Sacramento, CA: California Air Resource Board.

———. 2010. *California Exhaust Emission Standards and Test Procedures for 2001 and Subsequent Model Passenger Cars, Light-Duty Trucks, and Medium-Duty Vehicles.* As amended September 27, 2010. Sacramento, CA: California Air Resources Board

Consumer Reports. 2011. Annual Auto Issue. *Consumer Reports.*

DeCicco, J., and M. Thomas. 1999a. *Rating the Environmental Impacts of Motor Vehicles: The Green Guide to Cars and Trucks Methodology, 1999 Edition.* Washington, DC: American Council for an Energy-Efficient Economy.

———. 1999b. "A Method for Green Rating of Automobiles." *Journal of Industrial Ecology* 3(1): 55-75.

Delucchi, M.A. 2004. *The Annualized Social Cost of Motor-Vehicle Use in the United States, 1990–1991: Summary of Theory, Data, Methods, and Results.* UCD-ITS-RR96-3(1). Davis, CA: University of California, Institute of Transportation Studies.

———. 2005 (with updates from 2006). Lifecycle Emissions Model (LEM). Computer Spreadsheet. Davis, CA: University of California, Institute of Transportation Studies.

Delucchi, M.A., and D.R. McCubbin. 1996*. The Contribution of Motor Vehicles and Other Sources to Ambient Air Pollution.* UCD-ITS-RR96-3(16). Davis, CA: University of California, Institute of Transportation Studies.

———. 2010. External Costs of Transport in the U.S. Chapter in *Handbook of Transport Economics,* ed. by A. de Palma, R. Lindsey, E. Quinet, and R. Vickerman, Edward Elgar Publishing Ltd.

DeLuchi, M.A. 1991*. Emissions of Greenhouse Gases from the Use of Transportation Fuels and Electricity*. ANL/ESD/TM 22. Argonne, IL: Argonne National Laboratory, Center for Transportation Research.

DOE. 2010. *Model Year 2011 Fuel Economy Guide.* Washington, DC: U.S. Department of Energy.

DOT. 2006. *Vehicle Survivability and Travel Mileage Schedules*. Washington, DC: U.S. Department of Transportation, National Highway Traffic Safety Administration.

———. 2009. "Average Fuel Economy Standards Passenger Cars and Light Trucks, Model Year 2011." *Federal Register* 74 (59).

Elgowainy, A., Han, J., Poch, L., Wang, M., Vyan, A. Mahalik, M., and Rousseau A. 2010. *Well-to-Wheels Analysis of Energy Use and Greenhouse Gas Emissions of Plug-In Hybrid Electric Vehicles.* Chicago, IL: U.S. Department of Energy.

EIA. 2010. Combined Utility, Non-Utility & Combined Heat and Power Plant Data, 2009. http://www.eia.gov/cneaf/electricity/page/eia906_920.html. Accessed August.

EPA. 1993a. *Status Report on the Use of Environmental Labels Worldwide.* EPA 742-R-93-001. Washington, DC: U.S. Environmental Protection Agency, Office of Pollution Prevention and Toxics.

———. 1993b. *The Use of Life-Cycle Assessment in Environmental Labeling.* EPA 742-R-93-003. Washington, DC: U.S. Environmental Protection Agency, Office of Pollution Prevention and Toxics.

———. 2000. "Control of Air Pollution from New Motor Vehicles: Tier 2 Motor Vehicle Emissions Standards and Gasoline Sulfur Control Requirements; Final Rule." Federal Register 65 (28): 6698-6746.

———. 2003. *MOBILE6.1 Particulate Emission Factor Model Technical Description: Final Report*. EPA 420-R-03-001. Ann Arbor, MI: U.S. Environmental Protection Agency.

———. 2006a. "Fuel Economy Labeling of Motor Vehicles. Revisions to Improve Calculation of Fuel Economy Estimates; Final Rule." Federal Register 71 (248): 77872-77969.

———. 2006b. Fuel Economy Labeling of Motor Vehicles – Revisions to Improve Calculation of Fuel Economy Estimates, Final Technical Support Document. EPA-420-R-06-017. Washington DC: U.S. Environmental Protection Agency.

———. 2009a. Spreadsheet "Updated Optimization Model for Emissions of Greenhouse Gases from Automobiles (OMEGA) Post-Processor Spreadsheet for Final Rulemaking (FRM)." Available at www.regulations.gov. EPA-HQ-OAR-2009-0472-11448.

———. 2009b. *Development of Emissions Rates for Light-Duty Vehicles in the Motor Vehicle Simulator (MOVES2009).* EPA-420-P-09-002. Washington, DC: U.S. Environmental Protection Agency.

--------. 2009c*. Development of Evaporative Emissions Calculations for the Motor Vehicle Emissions Simulator (Draft MOVES2009).* EPA-420-P-09-006. Washington, DC: U.S. Environmental Protection Agency.

--------. 2010. *Conversion Factors for Hydrocarbon Emissions Components.* Report No. NR-002d. (July). Office of Transportation and Air Quality. Washington, D.C.: U.S. Environmental Protection Agency.

EPA/DOT. 2010. "Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards; Final Rule." *Federal Register* 75 (88): 25324-25728.

———. 2011. "Revisions and Additions to Motor Vehicle Fuel Economy Label; Final Rule." *Federal Register* 76 (129): 39478-39587.

FTC. 1996. *Labeling Alternative Fueled Vehicles: A Guide for Manufacturers, Conversion Companies, and Retailers of Alternative Fueled Vehicles.* Washington, DC: Federal Trade Commission, Bureau of Consumer Protection.

Gillis, J. 1999. *The Ultimate Car Book: 2000 Edition.* New York, NY: Harper Collins.

ICCT. 2010*. Comments on Revisions and Additions to Motor Vehicle Fuel Economy Label Proposed Rule.* International Council on Clean Transportation. http://www.theicct.org/info/documents/ICCT_cmnts_2010FElabel_proposal.pdf.

Kahan, A. 2010. Personal communication with Therese Langer. Washington, DC: U.S. Environmental Protection Agency. October.

Kliesch, J. 2004. *Rating the Environmental Impacts of Motor Vehicles: ACEEE's Green Book® Methodology, 2004 Edition*. Washington DC: American Council for an Energy-Efficient Economy

OMB. 2005. *Validating Regulatory Analysis: 2005 Report to Congress. Appendix B.* Washington, DC: Office of Management and Budget, Office of Information and Regulatory Affairs.

Ottinger, R.L. (ed.). 1991. *Environmental Costs of Electricity.* Prepared by the Pace University Center for Environmental Legal Studies. New York: Oceana Publications.

Ross, M., R. Goodwin, R. Watkins, M.Q. Wang, and T. Wenzel. 1995. *Real-World Emissions from Model Year 1993, 2000 and 2010 Passenger Cars*. Report prepared for The Energy Foundation, Washington, DC: American Council for an Energy-Efficient Economy.

SAE. 2010. Surface Vehicle Information Report "Utility Factor Definitions for Plug-In Hybrid Electric Vehicles Using Travel Survey Data. J2841 Sep2010. Society of Automotive Engineers.

Vaidyanathan, S., T. Langer, & S. Khan. 2010. *Proposed Updates to ACEEE's Green Book® Rating System for Model Year 2011*. Washington DC: American Council for an Energy-Efficient Economy.

Wang, M.Q., and D.J. Santini. 1995. "Monetary Values of Air Pollutant Emissions in Various U.S. Regions." *Transportation Research Record* 1475: 33-41.

WRI. 2010. Global Ecolabel Monitor 2010. Report prepared by BigRoom, Inc., in collaboration with WRI. Washington, DC: World Resources Institute. www.ecolabelindex.com/downloads/Global_Ecolabel_Monitor2010.pdf.

# APPENDIX A. GREEN BOOK 2011 TAILPIPE EMISSIONS

### Appendix Table A1:
### Tier 2 Vehicle Tailpipe Emissions (g/mi)

| | LDV/LDT/MDPV | | | |
|---|---|---|---|---|
| | CO | NMOG | $NO_x$ | $PM_{10}$ [c] |
| bin 1 [b] | 0.0 | 0.0 | 0.0 | 0.0 |
| bin 2 [b] | 1.7 | 0.007 | 0.014 | 0.01 |
| bin 3 [b] | 1.7 | 0.04 | 0.021 | 0.01 |
| bin 4 [b] | 1.7 | 0.051 | 0.029 | 0.01 |
| bin 5 [a] | 3.4 | 0.075 | 0.05 | 0.01 |
| bin 6 [a] | 3.4 | 0.075 | 0.08 | 0.01 |
| bin 7 [a] | 3.4 | 0.075 | 0.11 | 0.02 |
| bin 8 [a] | 3.4 | 0.1 [d] | 0.14 | 0.02 |

a. These are the Tier 2 50,000-mile standards for CO, NMOG and $NO_x$ (EPA 2000).
b. Tier 2 does not set 50,000-mile standards for bins 1-4; we generated the values shown by scaling down the 120,000-mile standards. Therefore, we scaled the full lifetime standards for these bins by the ratio between 50,000-mile and 120,000-mile standards from bins 5-8.
c. Tier 2 does not set 50,000-mile standards for PM; the value shown is the 120,000-mile standard.
d. Larger bin 8 trucks (over 6,000 lbs. GVWR) in the 2011 Green Book were mistakenly assigned NMOG emissions of 0.125 g/mi, reflecting a Tier 2 provision that expired in 2008.

### Appendix Table A2:
### LEV II Vehicle Tailpipe Emissions (g/mi)

| | LDV/LDT/MDV 2&3 | | | | MDV (2b) | | | |
|---|---|---|---|---|---|---|---|---|
| | CO | NMOG | $NO_x$ | $PM_{10}$ [b] | CO | NMOG | $NO_x$ | $PM_{10}$ [b] |
| ZEV | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| PZEV [c] | 0.645 | 0.006 | 0.011[c] | 0.01 | 3.2 | 0.1 | 0.1 | 0.06 |
| SULEV II [b] | 0.81 | 0.007 | 0.014 | 0.01 | 3.2 | 0.1 | 0.1 | 0.06 |
| ULEV II [a] | 1.7 | 0.04 | 0.05 | 0.01 | 6.4 | 0.143 | 0.2 | 0.06 |
| LEV II [a] | 3.4 | 0.075 | 0.05 | 0.01 | 6.4 | 0.195 | 0.2 | 0.12 |

a. These are the LEV II 50,000-mile standards for CO, NMOG and $NO_x$ (CARB 2010).
b. The LEV II program does not set 50,000-mile standards for SULEVs; we generated the values shown for light-duty vehicles by scaling down the 120,000-mile standards. LEV II also does not set 50,000-mile PM standards for any bin; the value shown in the 120,000-mile standard.
c. 50,000-mile standards for PZEV vehicles were further scaled using the ratio between 50,000- and 120,000-mile standards for LEV II and ULEV II.
d. PZEVs were mistakenly scored at a $NO_x$ level of 0.02 for MY2011. This increased EDX by less than one percent.

# APPENDIX B. EVALUATION OF IMPACTS FROM VEHICLE MANUFACTURING AND DISPOSAL (EMBODIED EMISSIONS)

**Appendix Table B1. Internal Combustion Engines**

| | Pollutant | Intercept (grams per vehicle per lifetime) | Weight Coefficient (grams per lb of vehicle) |
|---|---|---|---|
| Cars | GHGs | 1,367,377 | 2,432 |
| | $CO_2$ | 1,308,331 | 2,309 |
| | $PM_{10}$ | 1,791 | 4.04 |
| | $NO_x$ | 3,171 | 3.75 |
| | CO | 987 | 12.04 |
| | $SO_x$ | 4,368 | 6.75 |
| SUVs | GHGs | 1,695,557 | 2,323 |
| | $CO_2$ | 1,623,295 | 2,205 |
| | $PM_{10}$ | 2,234 | 3.91 |
| | $NO_x$ | 3,917 | 3.52 |
| | CO | 840 | 11.95 |
| | $SO_x$ | 5,535 | 6.19 |
| Pick-ups | GHGs | 1,695,308 | 2,230 |
| | $CO_2$ | 1,623,064 | 2,147 |
| | $PM_{10}$ | 2,227 | 3.98 |
| | $NO_x$ | 3,916 | 3.52 |
| | CO | 836 | 11.99 |
| | $SO_x$ | 5,538 | 6.15 |

**Appendix Table B2(a). Hybrid-Electric Vehicles (Nickel Metal Hydride Batteries)**

| | Pollutant | Intercept (grams per vehicle per lifetime) | Weight Coefficient (grams per lb of vehicle) [a] | Battery Weight Coefficient (grams per lb of battery) |
|---|---|---|---|---|
| Cars | GHGs | 1,287,797 | 2,084 | 12,206 |
| | $CO_2$ | 1,272,024 | 1,976 | 11,185 |
| | PM10 | 1,715 | 3.47 | 15.21 |
| | $NO_x$ | 3,067 | 2.83 | 12.94 |
| | CO | 1,134 | 12.42 | -0.08 |
| | $SO_x$ | 6,269 | 7.30 | 104.55 |
| SUVs | GHGs | 1,590,442 | 1,952 | 12,233 |
| | $CO_2$ | 1,521,653 | 1,850 | 11,780 |
| | $PM_{10}$ | 2,138 | 3.34 | 15.21 |
| | $NO_x$ | 3,776 | 2.54 | 12.98 |
| | CO | 1,047 | 12.41 | -0.23 |
| | $SO_x$ | 5,089 | 6.86 | 126.96 |
| Pick-ups | GHGs | 1,590,807 | 1946.68 | 12,239 |
| | $CO_2$ | 1,522,012 | 1844.91 | 11,786 |
| | $PM_{10}$ | 2,136 | 3.36 | 15.19 |
| | $NO_x$ | 3,777 | 2.53 | 12.99 |
| | CO | 1,036 | 12.56 | -0.39 |
| | $SO_x$ | 4,240 | 7.45 | 110.83 |

a. The weight coefficient shows the impact of total vehicle weight (including battery weight) on emissions output.

**Appendix Table B2(b). Hybrid-Electric Vehicles (Lithium-ion Batteries)**

| | Pollutant | Intercept (grams per vehicle per lifetime | Weight Coefficient (grams per lb of vehicle) [a] | Battery Weight Coefficient (grams per lb of battery) |
|---|---|---|---|---|
| Cars | GHGs | 1,287,797 | 2,084 | 5,421 |
| | $CO_2$ | 1,231,422 | 1,977 | 5,224 |
| | $PM_{10}$ | 1,715 | 3.47 | 6.79 |
| | $NO_x$ | 3,067 | 2.83 | 6.38 |
| | CO | 1,133 | 12.42 | -10.06 |
| | $SO_x$ | 4,036 | 7.59 | 44.93 |

a. The weight coefficient shows the impact of total vehicle weight (including battery weight) on emissions output.

**Appendix Table B3. Electric Vehicles (Lithium-ion Batteries)**

| | **Pollutant** | **Intercept (grams per vehicle per lifetime** | **Weight Coefficient (grams per lb of vehicle) [a]** | **Battery Weight Coefficient (grams per lb of battery)** |
|---|---|---|---|---|
| Cars | GHGs | 1,034,184 | 1,943 | 5,446 |
| | $CO_2$ | 987,060 | 1,842 | 5,247 |
| | $PM_{10}$ | 1,576 | 3.14 | 7.03 |
| | $NO_x$ | 2,640 | 2.56 | 6.43 |
| | CO | 1,128 | 12.84 | -10.51 |
| | $SO_x$ | 3,579 | 6.36 | 45.90 |

a. The weight coefficient shows the impact of total vehicle weight (including battery weight) on emissions output.

# APPENDIX C. ENVIRONMENTAL DAMAGE INDEX (EDX) CALCULATIONS

## Appendix Table C1. EDX Calculation for an Average 2011 Car

**Vehicle Attributes**[‡]

| | |
|---|---|
| Emissions Standard | ULEV II / Tier 2 bin 5 |
| Fuel Economy | 25.6 mpg (combined adjusted) |
| Est. Curb Wt. | 3,200 lb. |

(**a) Emissions at the Vehicle**

| **Regulated Emissions** (by species) | Emission Standard (grams/mile)[†] | Damage Cost ($/kg) | Life Cycle Cost (cents/mile) |
|---|---|---|---|
| CO | 1.7 | 0.04 | 0.0071 |
| HC | 0.04 | 0.47 | 0.0019 |
| $NO_X$ | 0.05 | 6.24 | 0.0312 |
| $PM_{10}$ | 0.01 | 50.09 | 0.0501 |

| **Fuel-Dependent Emissions** (by species) | Emission Factor (grams/gallon) | Emissions Rate (grams/mile) | Damage Cost ($/kg) | Life Cycle Cost (cents/mile) |
|---|---|---|---|---|
| Evaporative HC[¤] | -- | -- | 0.47 | -- |
| $SO_X$ | 0.194 | 0.008 | 29.42 | 0.022 |
| $CH_4$ | 1.26 | 0.049 | --* | |
| $N_2O$ | 1.67 | 0.065 | --* | |
| $CO_2$ | 8856 | 345 | --* | |

**Subtotal (a): health-related pollution impacts at the vehicle (cents/mile) 0.112**

**(b) Emissions from the Fuel Supply Cycle**

| **Fuel-Dependent Emissions** (by species) | Emission Factor (grams/gallon) | Emissions Rate (grams/mile) | Damage Cost ($/kg) | Life Cycle Cost (cents/mile) |
|---|---|---|---|---|
| CO | 8.35 | 0.33 | 0.008 | 0.000271 |
| HC | 6.05 | 0.24 | 0.094 | 0.002 |
| $NO_X$ | 9.93 | 0.39 | 1.25 | 0.048 |
| $PM_{10}$ | 0.42 | 0.02 | 10.02 | 0.016 |
| $SO_X$ | 7.70 | 0.30 | 5.89 | 0.177 |
| $CH_4$ | 27.73 | 1.08 | --* | |
| $N_2O$ | 0.14 | 0.01 | --* | |
| $CO_2$ | 2308 | 90 | --* | |

**Subtotal (b): health-related pollution impacts from fuel supply (cents/mile) 0.244**

[‡] The Average MY2011 Car was selected as the actual light-duty vehicle most closely matching both fuel economy and vehicle weight estimates as identified in EPA (2010). This year, the Average Car is a 2011 Ford Fusion, 2.5L 4-cylinder, semi-automatic transmission, with labeled fuel economy of 22/30 mpg (city/hwy) and inertial test weight (ITW) of 3500 lb. Based on analysis of the model year 2011 passenger car fleet, a joint certification of Tier 2 bin 5 and ULEV II was selected as the most representative emissions standard.

[†] The emission standards listed in part (A) are 50,000 mile standards.

[¤] Evaporative emissions were not included in the 2011 Green Book.

[*] Greenhouse gases are not assigned a health damage cost; these emissions are incorporated on the following page, in part (e).

**Appendix Table C1. EDX Calculation for an Average 2011 Car (continued)**

**(c) Emissions Embodied in the Vehicle (materials, assembly, recycling, disposal)**

| **Species** | Total Emissions (grams) | Emissions Rate (grams/mi) | Damage Cost ($/kg) | Life Cycle Cost (cents/mile) |
|---|---|---|---|---|
| $NO_X$ | 11,490 | 0.096 | 1.25 | 0.015 |
| $PM_{10}$ | 12,631 | 0.105 | 10.02 | 0.129 |
| $SO_X$ | 20,918 | 0.174 | 5.88 | 0.125 |
| $CO_2$ | 7,183,601 | 59.863 | --* | |

**Subtotal (c): health-related pollution impacts from embodied emissions (cents/mile) 0.269**

**(d) Greenhouse Gas Emissions from all Sources**

| source: **Species** | At Vehicle (grams/mile) | Fuel Cycle (grams/mile) | Embodied (grams/mile) | Global Warming Potential (GWP) | $CO_2$-Equiv. (Grams/Mile) |
|---|---|---|---|---|---|
| $CO_2$ | 345.31 | 89.99 | 77.05 | 1 | 512.35 |
| HC | 0.04 | 0.24 | | 2 | 0.55 |
| $NO_X$ | 0.05 | 0.39 | | 4 | 1.75 |
| CO | 1.70 | 0.33 | | 5 | 10.13 |
| $CH_4$ | 0.05 | 1.08 | | 22 | 24.87 |
| $N_2O$ | 0.07 | 0.01 | | 355 | 25.11 |
| Sum weighted by GWP | 378.3 | 119.42 | 77.05 | | |

| | |
|---|---|
| Total $CO_2$-equivalent GHG emissions, grams per mile: | 574.8 |
| Assumed damage cost factor for GHG emissions, per kg $CO_2$-equivalent: | 0.0237 |
| **Subtotal (d): GHG impacts (cents/mile)** | **1.363** |

**(e) Summary of EDX Calculation for an Average 2011 Car**

| Environmental Impact | Life Cycle Cost (cents/mile) |
|---|---|
| (a) At the vehicle health-related pollution | 0.112 |
| (b) Fuel cycle health-related pollution | 0.244 |
| (c) Embodied health-related pollution | 0.269 |
| Subtotal, health-related pollution (criteria emissions) impacts | 0.625 |
| (d) Greenhouse gas impacts | 1.363 |
| **TOTAL Environmental Damage Index (EDX)** | **1.99** |
| **Corresponding MY2011 Green Score** | **41** |

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[*] Greenhouse gases are not assigned a health damage cost; these emissions are incorporated on the following page, in part (e).

### Appendix Table C2. (EDX) Calculation for an Average 2011 Light Truck

**Vehicle Attributes**[‡]

| | |
|---|---|
| Emissions Standard | Tier 2 bin 5 / ULEV II |
| Fuel Economy | 18.9 mpg (combined adjusted) |
| Est. Curb Wt. | 4,500 lb. |

**(a) Emissions at the Vehicle**

| **Regulated Emissions** (by species) | Emission Standard (grams/mile) [†] | Damage Cost ($/kg) | Life Cycle Cost (cents/mile) |
|---|---|---|---|
| CO | 1.7 | 0.04 | 0.0071 |
| HC | 0.04 | 0.47 | 0.0019 |
| $NO_X$ | 0.05 | 6.24 | 0.0312 |
| $PM_{10}$ | 0.01 | 50.09 | 0.0501 |

| **Fuel-Dependent Emissions** (by species) | Emission Factor (grams/gallon) | Emissions Rate (grams/mile) | Damage Cost ($/kg) | Life Cycle Cost (cents/mile) |
|---|---|---|---|---|
| Evaporative HC[¤] | -- | -- | 0.47 | -- |
| $SO_X$ | 0.194 | 0.010 | 29.42 | 0.030 |
| $CH_4$ | 1.26 | 0.067 | --* | |
| $N_2O$ | 1.67 | 0.089 | --* | |
| $CO_2$ | 8856 | 469.368 | --* | |

**Subtotal (a): health-related pollution impacts at the vehicle (cents/mile) 0.120**

**(b) Emissions from the Fuel Supply Cycle**

| **Fuel-Dependent Emissions** (by species) | Emission Factor (grams/gallon) | Emissions Rate (grams/mile) | Damage Cost ($/kg) | Life Cycle Cost (cents/mile) |
|---|---|---|---|---|
| CO | 8.35 | 0.44 | 0.008 | 0.00037 |
| HC | 6.05 | 0.32 | 0.094 | 0.0030 |
| $NO_X$ | 9.93 | 0.53 | 1.25 | 0.066 |
| $PM_{10}$ | 0.42 | 0.02 | 10.02 | 0.022 |
| $SO_X$ | 7.70 | 0.41 | 5.89 | 0.24 |
| $CH_4$ | 27.73 | 1.47 | --* | |
| $N_2O$ | 0.14 | 0.01 | --* | |
| $CO_2$ | 2308 | 122.32 | --* | |

**Subtotal (b): health-related pollution impacts from fuel supply (cents/mile) 0.331**

[‡] The Average MY2011 Light Truck was selected as the actual light-duty vehicle most closely matching both fuel economy and vehicle weight estimates as identified in EPA (2010). This year, the Average Light Truck is a 2011 Nissan Xterra, 4.0L 6-cyl, auto, with labeled fuel economy of 16/20 mpg (city/hwy) and inertial test weight (ITW) of 3500 lb. Based on analysis of the model year 2011 light truck fleet, a joint certification of Tier 2 bin 5 and ULEV II was selected as the most representative emissions standard.

[†] The emission standards listed in part (A) are 50,000 mile standards.

[¤] Evaporative emissions were not included in the 2011 Green Book.

[*] Greenhouse gases are not assigned a health damage cost; these emissions are incorporated on the following page, in part (e).

### (c) Emissions Embodied in the Vehicle (materials, assembly, recycling, disposal)

| **Species** | Total Emissions (grams) | Emissions Rate(grams/mi) | Damage Cost ($/kg) | Life Cycle Cost (cents/mile) |
|---|---|---|---|---|
| $NO_X$ | 15,032 | 0.125 | 1.25 | 0.018 |
| $PM_{10}$ | 17,142 | 0.143 | 10.02 | 0.163 |
| $SO_X$ | 26,702 | 0.223 | 5.88 | 0.156 |
| $CO_2$ | 9,591,725 | 79.931 | --* | |

**Subtotal (c): health-related pollution impacts from embodied emissions (cents/mile) 0.337**

### (d) Greenhouse Gas Emissions from all Sources

| source: **Species** | At Vehicle (grams/mile) | Fuel Cycle (grams/mile) | Embodied (grams/mile) | Global Warming Potential (GWP) | $CO_2$-Equiv. (Grams/Mile) |
|---|---|---|---|---|---|
| $CO_2$ | 469.37 | 122.32 | 96.42 | 1 | 688.11 |
| HC | 0.04 | 0.32 | | 2 | 0.72 |
| $NO_X$ | 0.05 | 0.53 | | 4 | 2.30 |
| CO | 1.70 | 0.44 | | 5 | 10.71 |
| $CH_4$ | 0.07 | 1.47 | | 22 | 33.81 |
| $N_2O$ | 0.09 | 0.01 | | 355 | 34.13 |
| Sum weighted by GWP | 511.0 | 162.32 | 96.42 | | |

| | |
|---|---|
| Total $CO_2$-equivalent GHG emissions, grams per mile: | 769.8 |
| Assumed damage cost factor for GHG emissions, per kg $CO_2$-equivalent: | 0.0237 |
| **Subtotal (d): GHG impacts (cents/mile)** | **1.826** |

### (e) Summary of EDX Calculation for an Average 2011 Light Truck

| Environmental Impact | Life Cycle Cost (cents/mile) |
|---|---|
| (a) At the vehicle health-related pollution | 0.120 |
| (b) Fuel cycle health-related pollution | 0.331 |
| (c) Embodied health-related pollution | 0.337 |
| Subtotal, health-related pollution (criteria emissions) impacts | 0.788 |
| (d) Greenhouse gas impacts | 1.826 |
| **TOTAL Environmental Damage Index (EDX)** | **2.61** |

**Corresponding MY2011 Green Score 32**

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* Greenhouse gases are not assigned a health damage cost; these emissions are incorporated on the following page, in part (e).

# APPENDIX D. FUEL CONSUMPTION-DEPENDENT EMISSIONS FACTORS

### Appendix Table D1. Vehicle In-Use Emissions

**Emission Factors (a)**

| Pollutant (vehicle standard) | Gasoline (g/gal) | Diesel (g/gal) | CNG (g/gge) | Notes |
|---|---|---|---|---|
| HC evap | - | - | - | (b) |
| $SO_x$ | 0.19 | 0.12 | 0.034 | (c) |
| $CH_4$ | 1.26 | 0.89 | 19.42 | (c) |
| $N_2O$ | 1.67 | 0.60 | 1.29 | (c) |
| $CO_2$ | 8558 | 9936 | 6482 | (c) |

Notes:
Emission factors are derived from Delucchi (2005), with spreadsheet references given in brackets [ ], except as otherwise noted.

a. Gasoline and CNG values are per gallon of gasoline equivalent ("gge," 125,100 Btu/gal); diesel values are per gallon of diesel (138,700 Btu/gal).
b. Evaporative emissions were not included in 2011 Green Book.
c. Emissions estimates for $CH_4$, $N_2O$, and $CO_2$ were derived as follows: For gasoline, the values assume standard (not reformulated) gasoline [Vehicle Emissions: 72-84], and converted from g/mi to g/gal using Delucchi's fuel-specific calculated vehicle efficiency specified in Table Y-11 of the LEM (Delucchi 2005). The same procedure was followed for CNG and diesel vehicles. $SO_x$ emission factors are based on the sulfur content of the fuel, as given in Delucchi (2005).

### Appendix Table D2. Upstream Emissions from Fuel Production, Distribution, and Vehicle Refueling

| Pollutant | Gasoline (g/gal) | Diesel (g/gge) | CNG (g/gge) | Notes | Electricity (g/kWh) (i) |
|---|---|---|---|---|---|
| NMOG | 6.1 | 1.7 | 0.9 | (a) | 0.014 |
| $CH_4$ | 27.7 | 26.7 | 44.3 | (b) | 0.023 |
| CO | 8.4 | 7.7 | 4.5 | (c) | 0.158 |
| $N_2O$ | 0.14 | 0.11 | 0.04 | (d) | 0.008 |
| $NO_x$ | 9.9 | 9.0 | 7.8 | (e) | 0.861 |
| $SO_x$ | 7.7 | 7.3 | 1.9 | (f) | 0.914 |
| $PM_{10}$ | 0.4 | 0.3 | 0.3 | (g) | 0.075 |
| $CO_2$ | 2308 | 1669 | 1325 | (h) | 598 |

Notes:
Except for electricity, all values are from the Delucchi (2005) Lifecycle Emissions Model (LEM). Values given in g/MBtu (grams per million Btu) are converted to g/gge (grams per gallon of gasoline equivalent) using a higher heating value of 125,100 Btu/gal for gasoline.

a. NMOG: Table Y-17f
b. $CH_4$: Table Y-17b
c. CO: Table Y-17d
d. $N_2O$: Table Y-17c
e. $NO_x$: Table Y-17e
f. $SO_x$: Table Y-17g
g. $PM_{10}$: Table Y-17i
h. $CO_2$: Table Y-17a
i. These values are derived from Appendix Table D3 and are based on a national average generation mix. Additionally, these figures do not consider charging losses as charging losses are included in the electric vehicle efficiencies used as inputs to the Green Book model.

## Appendix Table D3. Emission Factors for Electric Vehicle Recharging

### Key Assumptions and Parameters:

| | Fossil Fuel Resource and Technology | | | | Electricity | |
|---|---|---|---|---|---|---|
| | Coal | Oil | Natural Gas Boiler | Natural Gas Turbine | Nuclear | |
| Generation Mix (a) | 44.64% | 0.98% | 8.36% | 14.92% | 20.21% | Average Net Efficiency: 31.10% |
| Generation Efficiency (b) | 33.66% | 30.33% | 34.53% | 34.53% | 32.64% | |
| Distribution Efficiency (c) | 93.85% | 93.85% | 93.85% | 93.85% | 93.85% | |

| Emission Rates (g/MBtu input) (d) | | | | |
|---|---|---|---|---|
| NMOG | 1.47 | 2.43 | 3.87 | 1.92 |
| $CH_4$ | 0.95 | 0.85 | 1.02 | 10.89 |
| CO | 11.86 | 15.15 | 24.01 | 49.90 |
| $N_2O$ | 0.95 | 0.33 | 0.63 | 2.00 |
| $NO_x$ | 153.73 | 42.53 | 23.90 | 59.60 |
| $SO_x$ | 185.76 | 149.90 | 0.16 | 0.16 |
| $PM_{10}$ | 8.40 | 11.71 | 3.38 | 19.01 |
| $CO_2$ (kg/MBtu) | 95.14 | 75.00 | 53.33 | 53.22 |

### Resulting Estimates:

| Emissions per unit of delivered power (g/MBtu) | Coal | Oil | Natural Gas Boiler | Natural Gas Turbine | National Average | Average g/kWh |
|---|---|---|---|---|---|---|
| NMOG | 4.65 | 8.54 | 11.94 | 5.92 | 4.04 | 0.014 |
| $CH_4$ | 3.00 | 2.98 | 3.16 | 33.59 | 6.65 | 0.023 |
| CO | 37.55 | 53.23 | 74.10 | 153.97 | 46.45 | 0.158 |
| $N_2O$ | 3.00 | 1.17 | 1.95 | 6.17 | 2.44 | 0.008 |
| $NO_x$ | 486.64 | 149.41 | 73.76 | 183.91 | 252.31 | 0.861 |
| $SO_x$ | 588.02 | 526.60 | 0.49 | 0.49 | 267.77 | 0.914 |
| $PM_{10}$ | 26.58 | 41.14 | 10.43 | 10.43 | 21.89 | 0.075 |
| $CO_2$ (kg/MBtu) | 301.16 | 263.50 | 164.56 | 164.56 | 175.28 | 598.056 |

| Nuclear Power Externality Cost | |
|---|---|
| Damage cost (¢/kWh) | 0.61 |
| Generation share | 20.21% |
| Cost (¢/kWh) | 0.12 |
| | |
| Non-nuclear electricity cost (¢/kWh) | 0.49 |
| Overall external electricity cost (¢/kWh) | 0.61 |

a. ACEEE calculations based on information at [http://www.eia.doe.gov/cneaf/electricity/page/eia906_920.html](http://www.eia.doe.gov/cneaf/electricity/page/eia906_920.html) for 2009 calendar year
b. ACEEE calculations based on information from the EIA at <http://www.eia.doe.gov/cneaf/electricity/epa/epat5p4.html>
c. ACEEE calculations based on information from <http://www.eia.doe.gov/cneaf/electricity/epa/epates2.html>
d. Delucchi 2005.

# APPENDIX E. VEHICLE INCLUSION AND CLASSIFICATION

The foundation for inclusion and classification of vehicles in *ACEEE's Green Book*® is the EPA database of models certified as meeting the applicable regulatory standards in the United States in a given model year. ACEEE provides ratings only for vehicles offered for general sale by established automakers having a mass-production track record. Concept vehicles, prototypes, and pre-market test products not yet offered for general sale will not be listed; neither will aftermarket devices or conversion vehicles, or other vehicles not certified under U.S. safety and emissions regulatory programs. Makes and models not included in the applicable government certification databases are not eligible for inclusion in *Green Book*®. Although ACEEE will attempt to rate all vehicles eligible as noted here, ACEEE cannot assure the listing of all vehicles that might be deemed eligible.

Classification is important to the presentation of environmental rating information, since the market is segmented into classes and consumers often compare a given model with others in its class. Yet no classification scheme is perfect. Class boundaries based on well-defined dimensions can result in seemingly arbitrary class distinctions among vehicles that fall near the boundaries. The market is, moreover, continuously evolving. A notable class that is important today, minivans, did not even exist 30 years ago. One of today's most popular segments, luxury sport utility vehicles, is a far cry from the utilitarian jeeps and work vehicles of the past. The lines between station wagons, minivans, and sport utilities can be quite fuzzy. These segments have been in flux, with emerging "crossover vehicles" such as Subaru's Forester. Because crossover vehicles don't fit exactly into the designated *Green Book* vehicle classes, they have been listed in the class to which they are most related, or that best reflects their position in the market.

The starting point for our classification scheme is the one used by EPA in its databases and as used in the annual *Fuel Economy Guide* (DOE 2010). This publication is generally released in October of the calendar year proceeding the nominal model year; for example, DOE (2010) is the *Model Year 2011 Fuel Economy Guide.* It defines car classes based on interior volume, with a body style distinction separating wagons from coupes and sedans, and it defines light truck classes based on body styles.

## Passenger Cars

For passenger cars, we use a slight aggregation of the EPA size classes. The EPA classification is based on the sum of passenger and luggage volume, with the specific volume cut-off for each class as specified in the *Fuel Economy Guide*. We combine Minicompacts and Subcompacts into a single class which we term Subcompact Cars. We combine Midsize Station Wagons and Large Station Wagons into a single class, which we term Midsize Wagons. The resulting classes are: Two Seaters, Subcompact Cars, Compact Cars, Midsize Cars, Large Cars, Small Wagons, and Midsize Wagons.

## Light-Duty Trucks

For light trucks, we significantly modify the EPA size classes, disaggregating vehicles further than is done in the *Fuel Economy Guide.* Wishing to better represent the characteristics of the vehicles from a market perspective, we adopt a classification similar to those in consumer guides such as *The Ultimate Car Book* (Gillis 1999) and *Consumer Reports* (2011).

**Pickups.** EPA classes divide pickups into Compact and Standard based on Gross Vehicle Weight Ratings. These definitions lead to trucks such as the Ford Ranger and Ford F-150 being classified together. To separate these clearly different market segments but still maintain a simple rating system, we classify pickups by their wheelbase (a specification routinely reported by manufacturers). We use the roughly bimodal distribution of pickups by wheelbase to classify pickups as either Compact (Chevrolet Colorado, Dodge Dakota, Ford Ranger) or Standard (Chevrolet Silverado, Dodge Ram, Ford F-150). In addition, we do not classify four-wheel drive (4wd) and two-wheel drive (2wd) pickups separately as in the EPA classification.

**Vans.** The *Fuel Economy Guide* divides vans into Passenger and Cargo categories, without clear distinctions. In this case, we largely abandon the EPA classifications. We again use wheelbase as a determinant and use the roughly bimodal distribution to classify vans as either Minivans or Large Vans. This classification is also consistent with the consumer guides.

**Sport Utility Vehicles.** We use an SUV classification scheme representative of market segments, distinguishing, for example, between vehicles such as the Ford Escape and the GMC Yukon. Again, wheelbase provides a good determinant. The three-class division (Compact, Midsize, and Large) used in *The Ultimate Car Book* has been well suited for classifying sport utility vehicles. Examples of Compact SUVs include the Ford Escape, and Toyota RAV4. Midsize SUVs include the Chevrolet Blazer and Jeep Grand Cherokee. Large SUVs, typically built on Standard Pickup frames, include the Chevrolet Suburban and Ford Expedition. We avoid a classification distinction between 4wd and 2wd, listing these drivetrain variants together within a given utility vehicle size class.

## Distributions of EDX by Vehicle Class

The distributions of EDX for all cars, all light trucks, and the overall model year 2011 light-duty fleet is given in Figure 1. Appendix Table E1 identifies the EDX cutpoints used to determine the symbolic within-class rankings assigned to vehicles in *ACEEE's Green Book*®, based on the criteria shown in Table 6.

**Appendix Table E1. Cutpoints Used to Determine Class Rankings for Model Year 2011 Vehicles**

| | **Class Ranking Upper Limits (EDX, ¢/mi)**[a] | | | | |
|---|---|---|---|---|---|
| **Vehicle Class** | Superior | Above Average | Average | Below Average | Inferior |
| Percentile Guideline | 95% + | 80%–95% | 35%–80% | 15%–35% | 0–15% |
| Two Seaters | 1.69 | 2.17 | 2.46 | 2.89 | >2.89 |
| Subcompact Cars | 1.61 | 1.78 | 2.32 | 2.54 | >2.54 |
| Compact Cars | 1.59 | 1.73 | 2.13 | 2.39 | >2.39 |
| Midsize Cars | 1.72 | 1.91 | 2.31 | 2.50 | >2.50 |
| Large Cars | 1.92 | 2.30 | 2.67 | 2.93 | >2.93 |
| Small Wagons | 1.67 | 1.86 | 2.08 | 2.35 | >2.35 |
| Midsize Wagons | 2.16 | 2.34 | 2.58 | 2.69 | >2.69 |
| Compact Pickups | 2.19 | 2.27 | 2.70 | 2.78 | >2.78 |
| Standard Pickups | 2.70 | 2.78 | 3.10 | 3.29 | >3.29 |
| Compact SUVs | 1.98 | 2.05 | 2.24 | 2.46 | >2.46 |
| Midsize SUVs | 2.17 | 2.34 | 2.67 | 2.89 | >2.89 |
| Large SUVs | 1.50 | 2.82 | 3.24 | 3.37 | >3.37 |
| Minivans | 2.26 | 2.38 | 2.41 | 2.41 | >2.41 |
| Large Vans | 3.20 | 3.21 | 3.59 | 3.75 | >3.75 |

Notes:

a. A vehicle is assigned a given class ranking if its environmental damage index (EDX) is less than the cutpoint for the ranking and, for a Superior ranking, if its Green Score is no less than the overall 2011 average of 34.8 (corresponding to the MY2011 combined car-truck average EDX of 2.42¢/mi).

## APPENDIX F. SUMMARY OF METHODOLOGY CHANGES SINCE 2004

A number of modifications to our environmental rating methodology have been made since the publication of the last methodology report for ACEEE's Green Book® (Kliesch 2004). Although the life-cycle assessment principles underlying Green Book methodology have largely remained constant between 2004 and 2011, a number of components were updated to take into account new research, new models and new technologies.

### Tier 2 Phase-In

Since the publication of the 2004 Green Book Methodology Report (Kliesch 2004), the federal Tier 2 program has been completely phased in. All new Tier 2 vehicles fall into bins 1-8; standards are uniform across vehicle class; and gasoline sulfur level (30 ppm) is now fixed over time.

### Emission Factors and Emission Standards

A major change to Green Book methodology for model year 2011 was the use of emission standards to score vehicles instead of real world emissions estimates. The switch was spurred in large part by EPA's transition from the MOBILE 6 model to the Motor Vehicle Emissions Simulator (MOVES), which does not report out emissions of vehicles by certification level (Tier 2 or LEV II bin). Certification level is an important input to Green Book's vehicle ratings.

Green Book emissions factors in prior years were largely based on runs of EPA's MOBILE model, which showed average emissions over the life of a vehicle substantially in excess of the full useful life standards defining the vehicle's Tier 2 or LEV II bin. Average emissions may exceed the standards in part because the standards pertain to performance over the Federal Test Procedure (FTP) cycle, which does not fully replicate real-world operation. In particular, operation at high speed, at low temperature, and using the air conditioner are not reflected in the bin certification levels. Some of these "off-cycle" emissions are captured by the Supplemental Federal Test Procedure (SFTP); but the corresponding supplemental standards are far above the standards defining the emissions bins and presumably are too high to provide a good estimate of average emissions.

Unlike MOBILE, MOVES does not directly produce a projection of how vehicles certified to a given emissions bin will perform over time. Instead, the emissions profile of the population of new vehicles of a given type in a given year is synthesized for MOVES using the expected sales breakdown by bin. This synthesis occurs outside the model (EPA 2009a).

A supplementary EPA analysis for the 2012-2016 greenhouse gas emissions rule for light-duty vehicles (EPA 2009a) used MOVES to show grams per mile emissions of post-2010 vehicles as a function of age. We computed lifetime average grams per mile emissions from cars using those emissions rates weighted by the expected miles driven per year over the lives of the vehicles. We compared these emissions rates to weighted full-life standards using EPA's projected distribution of car sales by Tier 2 bin for 2010 and beyond (approximately one percent bin 2, 37 percent bin 3, three percent bin 4, and 59 percent bin 5) (EPA 2009b). Figure 1 shows emissions rates for gasoline cars as calculated in these two ways.

**Figure F1. Grams per Mile for the Average New Car in 2010+: Lifetime Average from MOVES vs. Full-Life Standard**

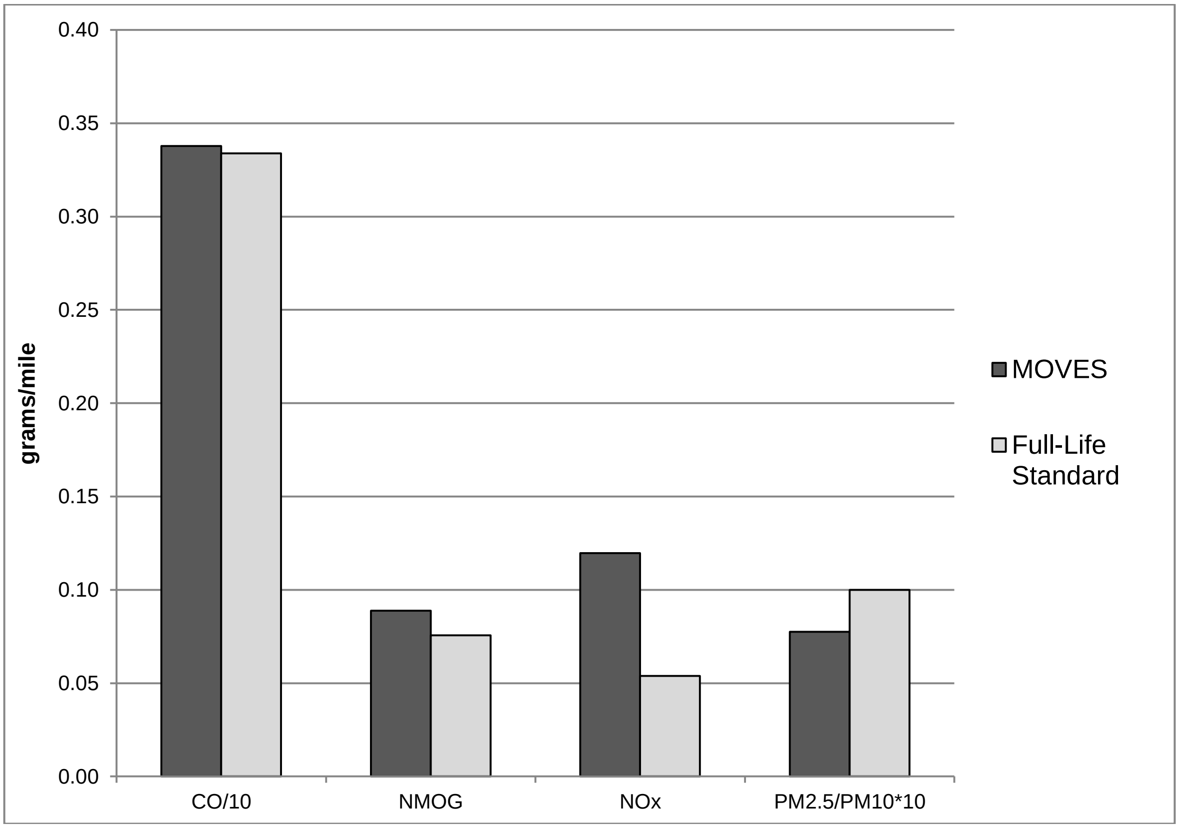

Figure 1 shows a reasonably good correspondence between the two sets of emissions rates for the given mix of emissions bins. In the case of NOx, however, average emissions as projected by MOVES are over twice as high as the average full-life standard to which the vehicles are certified. Hence using full-life certification values as lifetime emissions rates for gasoline cars may substantially understate NOx. The previous Green Book NOx emissions factor for this combination of bins is much higher still; but we have no basis for reverting to those MOBILE-based numbers, since MOVES supercedes MOBILE.

While the MOVES estimate of average PM emissions appears to be lower than the full-life standard, the comparison is not entirely valid. The MOVES results are for $PM_{2.5}$, while the standard is for $PM_{10}$. The vast majority of vehicle particulate emissions are $PM_{2.5}$, however.

A hallmark of Tier 2 standards, with the completion of their phase-in by MY 2009, is that requirements are the same for all vehicles in a given bin, regardless of class or fuel type. For a variety of reasons including those mentioned above, real-world emissions for vehicles within a bin may nonetheless vary with vehicle class and fuel.

Real-world emissions data for recent U.S. light–duty diesels are hard to come by, due in part to the small number of such vehicles sold. The same set of MOVES model outputs referenced above show $NO_x$ emissions for new diesels in excess of those for new gasoline vehicles. However, that analysis is based on extrapolation from the performance of diesels certified to bin 10 and in particular does not reflect any emissions data for today's bin 5 "clean diesels" nor the characteristics of these vehicles' emissions control systems. Absent data to the contrary, Green Book methodology now assumes that diesel vehicles will also emit at the levels of the standards to which they are certified.

We use standards to represent average in-use emissions not only for gasoline and diesel vehicles, but also for CNG vehicles.[2] As a result, impacts attributed to CNG vehicles have increased relative to those of other vehicles, because their emissions rates under the earlier Green Book methodology were below those of gasoline vehicles in the same bin, and in some cases well below the certification values.

Earlier Green Book emissions factors also varied with vehicle class. In general, larger vehicles had higher emissions factors at a given certification level. As a result, larger vehicles will tend to benefit more from the assumption that vehicles emit at the level of standards than will a smaller vehicle of the same certification level. At the same time, larger vehicles are certified more frequently to dirtier emissions levels, and the ratio of previous Green Book emissions rates to standards was generally lower for higher-emitting vehicles. Hence, how the net effect of this change in methodology varies by class is not obvious.

For MOVES, EPA computes real-world emissions using a characterization of operating modes based on vehicle-specific power (VSP). Truck driving patterns, including high speed and acceleration, result in higher VSP values and hence higher emissions (EPA 2009b, Kahan 2010). Therefore a truck having the same emissions as a car over the FTP test cycle can have much higher real-world emissions at high speeds, which would be reflected in emissions as calculated by MOVES.

Using the MOVES outputs referenced previously, we generated lifetime factors for light trucks. These were higher than car values by a factor of 1.7-1.8, with the exception of NOx, which was higher than the car value by a factor of 2.9. These factors may overstate light truck emissions by virtue of their inclusion of emissions of light heavy-duty trucks of Classes 2b-3 (Kahan 2010). Although these are far less numerous than light trucks under 8,500 lbs GVW, their emissions could appreciably raise average truck emissions.

Thus, while MOVES outputs indicate that light truck emissions may be substantially higher than car emissions at a given standard, we do not at this time have class- and bin-specific estimates of how much higher they are. We assume for the present that emissions are determined by the levels of the standards to which the vehicle is certified but plan to revisit this issue as more data on real-world emissions of new vehicles becomes available.

The use of emissions standards levels to represent in-use emissions is a major departure from earlier Green Book methodology. To evaluate the effects of this change on EDX, we reevaluated all 2010 vehicles, replacing the emissions rates from the 2010 Green Book methodology with emissions standards. This resulted in an average reduction of 12 percent in EDX. For a discussion of how results varied by technology and fuel type, by vehicle class, and by bin, see Vaidyanathan et al. (2010).

## Unregulated In-Use Vehicle Emissions

Emission factors for unregulated, in-use, fuel consumption-dependent pollutants have been updated using the 2005 edition of Delucchi's Lifecycle Emissions Model (LEM) (DeLucchi 2005). These pollutants include $SO_x$, $CH_4$, $N_2O$ and $CO_2$. In general, there is a drop in $CH_4$, and $N_2O$ emissions (on a grams/gge basis) for gasoline- and CNG-fueled vehicles, and a slight (one-half percent to four percent) increase in $CO_2$ emissions, depending upon fuel. The proposed increase in $CH_4$ and $N_2O$ emission factors for diesel-powered vehicles reflects the current LEM version's incorporation of light duty emission factors. (The prior corresponding diesel components were based on heavy duty modeling elements; see Kliesch 2004, Appendix Table B1).Emissions factors for $SO_x$ are much lower than modeled in previous years, reflecting the rapid decline in sulfur content of gasoline and diesel fuel that occurred with the phase in of EPA's Tier 2 rule. Factors for unregulated in-use emissions are shown below in Appendix Table D1.

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[2] The 2011 Green Book used 50,000 mile standards, rather than the full-life (120,000 miles) standards discussed in this section. See Areas for Future Work, above.

## Vehicle Life-Cycle Emissions Estimates

Another major change to Green Book methodology involves the use of Argonne National Laboratory's GREET 2.7 vehicle-cycle model to estimate manufacturing and disposal impacts, as described in the body of the report.

Green Book methodology previously estimated emissions associated with the materials production and manufacturing phases of vehicle life using vehicle weight together with the DeLuchi (1991) estimate of per-pound $CO_2$-equivalent emissions associated with manufacturing and the corresponding emissions of $NO_x$, $SO_2$, and $PM_{10}$. Batteries, including replacements, were treated as part of vehicle weight. In the most recent methodology, hybrid batteries were assumed to last the life of the vehicle based on comments we received on this point.

The previous methodology did not include emissions from vehicle recycling and disposal processes. GREET 2.7 includes recycling and disposal impacts and permits the incorporation of greater detail on key components, such as batteries, that differentiate the vehicle cycle impacts of more advanced vehicles from those of conventional vehicles.

In our updated methodology, vehicle weight remains the sole model-specific input determining vehicle cycle impacts for internal combustion engine vehicles. For hybrid electric vehicles (HEVs), plug-in hybrids and battery-electric vehicles, manufacturing and disposal impacts are determined by vehicle weight and battery weight and composition. GREET defaults include that NiMH batteries are replaced once over the life on a vehicle while Li-ion batteries last the life of the vehicle. We accepted these defaults for 2011, which meant that almost all hybrids were assumed to require replacement batteries, an assumption we will revisit in the next update (see Areas for Future Work, above).

The previous Green Book methodology accounted for environmental impacts beyond those associated with manufacturing-phase energy consumption by including the impacts of toxic pollutant releases and transfers from EPA's Toxic Releases Inventory (TRI) data. This year we did not incorporate these impacts, because they are not among GREET 2.7 outputs.

## Treatment of EVs and PHEVs

The arrival of the Chevrolet Volt and the Nissan Leaf on the U.S vehicle market necessitated an update to Green Book's treatment of electric vehicles. While we continue to utilize the existing methodology to rate electric vehicles, a number of changes have been made.

Grams per mile emissions from a vehicle running on electricity generated off-board are calculated as the product of the vehicle's average kilowatt hours (kWh) per mile and grams per kWh from power generation. For these vehicles, EPA listings include kWh per mile over the city and highway test cycles, i.e. the FTP and Highway Fuel Economy Test (HWFET) Cycles, respectively.

Just as for gasoline vehicles, however, these test values need to be adjusted to better represent typical energy usage, because there are major differences between real-world driving and the driving patterns reflected in the test cycles (EPA 2006b). Current Green Book methodology for gasoline and diesel vehicles reflects EPA's 2006 rule adjusting the calculation of real-world fuel economy for labeling purposes. This rule directs car manufacturers to test their vehicles in model year 2008 and beyond using a "five-cycle" test, comprising: the FTP Cycle, the HWFET Cycle, the US 06 Supplemental FTP Cycle to represent high speed aggressive driving, the SC 03 Supplemental FTP Cycle to represent the impact of air conditioner operation at high temperature, and a cold FTP Cycle to reflect the impact of cold temperatures.

For alternative fuel vehicles, including PHEVs and EVs, manufacturers have the option of using a "Derived 5-cycle" test (which was also an option for testing any vehicle through model year 2010), in which the new label city and highway fuel economy values are calculated from the original two-cycle test values alone. For high fuel economy vehicles, this yields severe corrections. We cap the derived 5-cycle adjustments at 30 percent, as was done in the 2011 EPA/DOT fuel economy labeling rule (EPA/DOT 2011).

Emissions from PHEV operation are the emissions associated with the operation of the ICE together with the emissions associated with the grid electricity used to power the vehicle. Thus, for model year 2011, we calculate PHEV emissions as the weighted sum of emissions associated with operation on the two power sources, where the weighting corresponds to the percentage of operation using each power source. The weighting for grid electricity is percentage of miles the vehicle is operated on electricity, or the utility factor (UF).

## U.S. Power Generation Characteristics

The U.S. power generation mix has changed significantly over the past decade. Coal generated power has decreased from 56 percent in 2001 to 45 percent in 2009 (EIA 2001, EIA 2010). On the other hand, power generation from natural gas has doubled from approximately 10 percent in 2001 to little more than 23 percent in 2009. Power generation from renewable energy sources increased from approximately 8 percent in 2001 to 10.5 percent in 2009. These changes are reflected in Green Book's analysis of plug-in vehicles' upstream emissions and manufacturing emissions impacts for all vehicle technologies.

Electricity generation emissions factors for NMOG, $CH_4$, CO, $N_2O$, NOx, SOx, $PM_{10}$, and $CO_2$ were updated using the latest version of the DeLucchi Life-cycle Emissions Model (2005). Using the newer emissions factors lead to an increase in emissions of NMOG, $CH_4$, CO, and $PM_{10}$, and a decrease in $N_2O$, NOx, SOx, and $CO_2$ for 2010.

## Upstream Emissions

Emission factors for upstream emissions have also been updated to values from the 2005 edition of Delucchi's LEM. These fuel-specific factors address a host of pollutants associated with the extraction, refining, and transporting of fuels from the well head to the fuel pump. While in some cases these numbers have noticeably changed, the expected effect of these changes on a typical vehicle's overall EDX is still expected to be modest. Proposed emission factors for upstream emissions are shown below in Appendix Table D2.

## Application of Green Scores to Dual Cert Vehicles

Over the past few years, most automakers have adopted an approach of dual-certifying single-hardware-spec vehicles to both a California and Federal (Tier 2) emissions standard to ease distribution efforts. Rather than listing two separate scorings of the vehicle performing under each of the certification levels, in model year 2006, we chose to list such vehicles with a single Green Score, reflecting the higher of the two scores. We continued this approach for model year 2007 and beyond.

This aggregation of vehicle listings makes it easier for consumers to identify the environmental performance of a particular vehicle on the showroom floor. The aggregation does not impact vehicles with separate hardware specs (where, for example, a PZEV version is sold with limited availability, and a Tier 2 bin 5 version is sold elsewhere); in such cases, two listings are still specified separately.