# Rating the Environmental Impacts of Motor Vehicles: ACEEE's greenercars.org Methodology
## 2016 Edition

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## Executive Summary

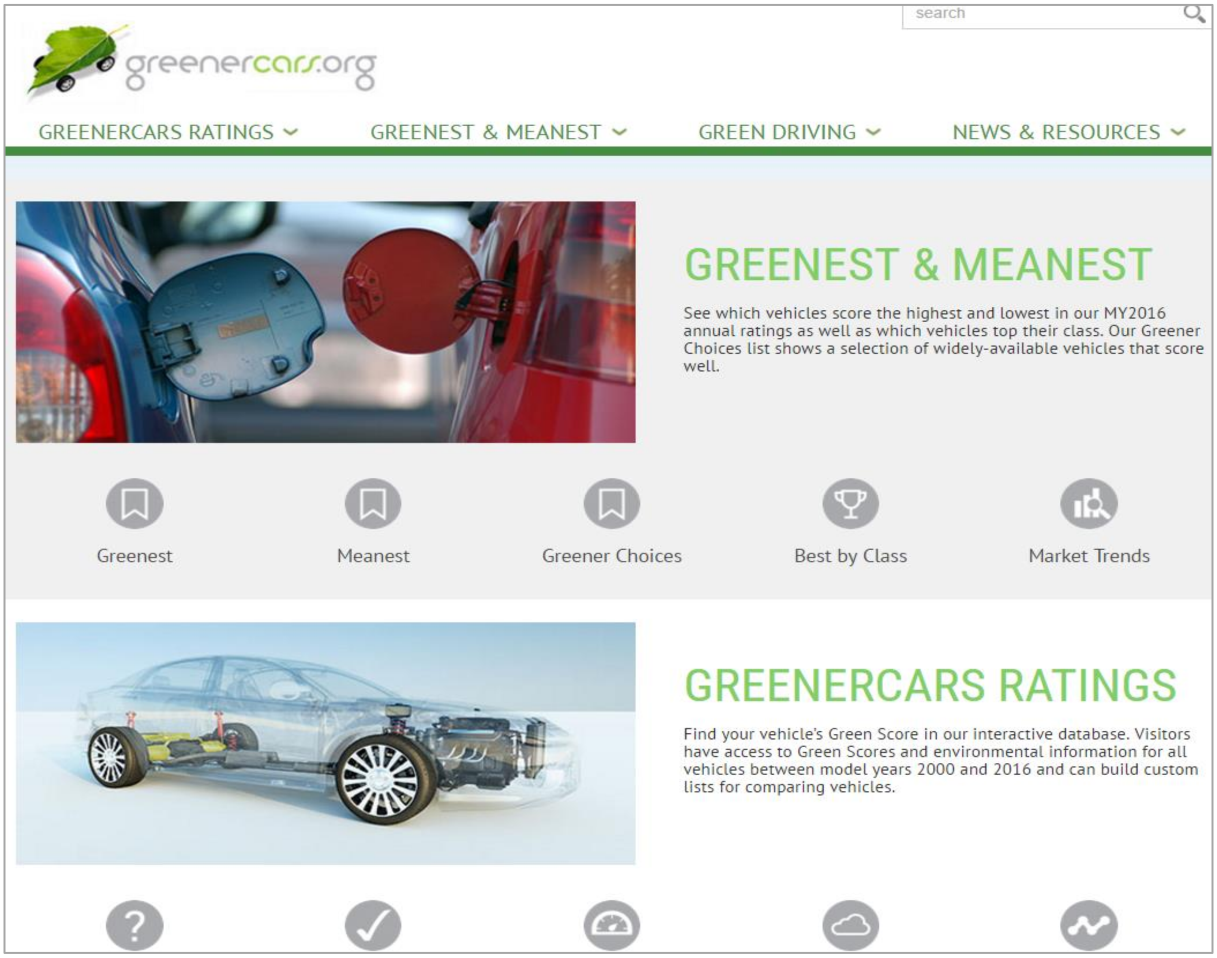
Consumer education and consumer incentive–based approaches to improving the environmental performance of automobiles require information that is easy to understand and readily accessible. Such information can influence both buyer decisions and manufacturers' technology and product planning activities. To provide such information, ACEEE publishes greenercars.org, an annual, consumer-oriented guide offering environmental ratings for every new model in the US light-duty vehicle market.

The environmental rating methodology for ACEEE's greenercars.org is based on principles of life cycle assessment and environmental economics. The methodology utilizes the limited data available by make and model in the US market. The approach estimates the impacts of criteria pollutant and greenhouse gas emissions, covering the vehicle life cycle and the full fuel cycle, including in-use emissions. This report covers the data issues, key assumptions, and analysis methods used to develop the vehicle ratings for greenercars.org. It summarizes the application of the current methodology, highlighting results for major classes and technology types, and identifies research needs for further updating and refining the methodology.

## 1. 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 consider 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 greenercars.org, that provides model-specific environmental information for the US automotive market (figure 1).



GREENEST & MEANEST

See which vehicles score the highest and lowest in our MY2016 annual ratings as well as which vehicles top their class. Our Greener Choices list shows a selection of widely-available vehicles that score well.

GREENERCARS RATINGS

Find your vehicle's Green Score in our interactive database. Visitors have access to Green Scores and environmental information for all vehicles between model years 2000 and 2016 and can build custom lists for comparing vehicles.

Figure 1. ACEEE greenercars.org website

This report covers the data issues, key assumptions, and methods used to develop the ratings that appear on ACEEE's greenercars.org. It documents the methodology, highlights results for major vehicle classes and technology types, and identifies research needs for updating and refining the methodology in the future. For background on the original development of this rating system and its policy context, see DeCicco and Thomas (1999a and 1999b).

## 2. Life Cycle Assessment of Emissions

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 and 1993b). In recent years, the number of eco-labels has proliferated, through both government-sponsored programs and numerous private and nonprofit sector initiatives (WRI 2010). For US light-duty vehicles, the Environmental Protection Agency's (EPA) fuel economy and environment label provides information about in-use GHG emissions and smog-forming pollutants (EPA and 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. The greenercars.org methodology considers only air pollution–related impacts. Additionally, only the use phase is well covered because it is the only part of the life cycle 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, although improvements in in-use efficiency mean that manufacturing and upstream fuel impacts play a larger role in vehicle pollution today. Use-phase shares vary by pollutant: they are high for carbon monoxide (CO), for example, but lower for sulfur dioxide ($SO_2$). With the phase-in of more stringent tailpipe standards in recent years, in-use emissions of criteria pollutants from gasoline-powered vehicles have declined more rapidly than other life cycle emissions, reducing their percentage contribution to total impacts. Battery electric vehicles, increasingly common 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

| | Phase of product life cycle | | | | |
|---|---|---|---|---|---|
| Environmental concern | Embodied: materials production | Embodied: product manufacture | Upstream | In use | Embodied: disposal |
| 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 | | | | | |

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 aggregate or uncertain data.

At present, only three types of relevant data cover all makes and models: (1) vehicle criteria emissions certification data, addressing use-phase emissions of several important air pollutants; (2) vehicle fuel economy and $CO_2$ emissions test data, addressing energy use and GHG emissions as well as providing information on unregulated use-phase air emissions; and (3) vehicle mass, partially addressing materials production, manufacturing, and disposal impacts. For fuel cell vehicles, fuel cell size data are available, and for hybrid-electric and plug-in electric vehicles, battery weight and composition are 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.

## *A. VEHICLE IN-USE EMISSIONS*

Automotive emissions of criteria air pollutants (six pollutants for which the Clean Air Act requires 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 (NOx), and particulate matter (PM), among other pollutants. 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 and other sources of evaporative emissions. Testing is the responsibility of automakers, who report the results to EPA and the California Air Resources Board (CARB). The agencies test a subset of new models for tailpipe emissions each year as part of their certification activities.

Historically, standard emissions tests have tended to under-predict in-use criteria 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 recent discovery that many of Volkswagen's diesel vehicles emit nitrogen oxides up to 40 times the certified level during normal operation, thanks to the use of defeat devices that turn off emissions control technologies in favor of improved fuel economy, further supports the notion that there is a significant difference between real-world and test cycle emissions. The reliability of a vehicle's emissions control system (ECS) and the trade-offs among emissions, fuel economy, and power play huge roles in determining 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 greenercars.org ratings 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. In-use data for newer vehicles, with more sophisticated ECS and cleaner fuels, have not been adequate to allow us to assign categorical and fuel-specific real-world values to vehicles, and consequently from model year 2011 onward our ratings have assumed 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.

Vehicle certification testing for GHG emissions (and fuel economy) also underestimates emissions. EPA certifies GHG emissions (in grams per mile) using the criteria pollutant emissions test cycle, which is intended to represent urban driving, together with a highway driving cycle. Vehicles are labeled for GHG emissions and fuel economy based on these results and additional test results, because the tests used to certify fuel economy are not adequate to represent actual on-road driving. For GHGs, the gap between test and real-world values is better understood and is corrected for on the vehicle label. For criteria pollution, we describe the additional tests in section 4a (i). Special requirements exist for the labeling of vehicles powered by electricity or other alternative fuels (FTC 1996; EPA and DOT 2011).

### *B. UPSTREAM EMISSIONS*

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, gasoline and diesel require extraction, refining, and distribution, all of which generate emissions. Grid-connected electric vehicles and fuel cell vehicles, which have no tailpipe emissions, give rise to a variety of emissions elsewhere in the fuel cycle, depending on how the electricity or hydrogen they consume 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 on the whole, based on national statistics. However some fuel cycle emissions, such as feedstock-related emissions for electricity and methane leakage associated with the production and distribution of natural gas, are incompletely documented and in flux.

Thus, given fuel economy data, estimating a vehicle's fuel supply cycle impacts on the basis of national averages enables greenercars.org to discriminate among models powered by different fuels. However as indicated by the B ratings for fuel cycle impacts in table 1, the estimates are not as robust as those for use-phase $CO_2$ emissions, for example.

### *C. EMBODIED 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. Model-specific data on manufacturing impacts and materials content are not available. Vehicle weight is the only specification affecting embodied impacts that is publicly available for every model on the market.

In 2007, Argonne National Laboratory (ANL) released the GREET 2 model, which quantifies the energy use and emissions associated with vehicle production and recycling and disposal (referred to as vehicle cycle emissions by ANL). GREET 2 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 embodied emissions impacts by model can be obtained by using vehicle weight as the primary GREET 2 input while using default values for the remaining parameters such as vehicle materials composition and fluid weight (ANL 2012b). As manufacturers turn increasingly to materials substitution to reduce vehicle weight, the ability to distinguish among vehicles' differing compositions becomes more important for evaluating embodied emissions impacts. However these data are not currently available on a model-by-model basis.

## 3. Greenercars.org Environmental Damage Index

In essence, the greenercars.org rating system is based on performing a limited LCA for each car and light truck model 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:

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

In principle, impacts could include any of those listed in table 1. We adopt a valuation based on environmental economics that uses monetized damage functions so that the EDX expresses an expected life cycle environmental cost of the vehicle. However this approach has its limitations. Dollar-based damage functions can never capture the full value to society of human life, health, and quality of life, nor can it account for ecological effects or the moral dimensions of environmental harms. Therefore, greenercars.org strictly considers the human health impacts of air pollution since we feel human health is the most important impact of vehicle-related air pollution. Additionally, the costs of human health impacts far exceed the combined costs of other impacts (Delucchi and McCubbin 2010). 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:

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

where i is an index over emissions 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).

## 4. Characterization of Impacts

Given the data availability as noted above, the greenercars.org methodology calculates the relation $EDX = \sum d_{ij}e_{ij}$ on the basis of vehicle in-use emissions, fuel cycle emissions, and emissions based on vehicle mass and mass of selected components (for embodied emissions).

### *A. IN-USE EMISSIONS*

Some vehicle emissions are regulated and others are not. We estimate both. Regulated tailpipe emissions include carbon monoxide (CO), non-methane organic gases (NMOG), hydrocarbons (HC), nitrogen oxides (NOx), and particulate matter.[1] These emissions depend on the emissions standard to which a vehicle is certified. Vehicles can be certified to either federal or California emissions standards, although most vehicles on the market today have dual certification. While the federal and California programs look largely similar, there is one key difference: California regulates the total non-methane organic gases (NMOG) under the Low Emission Vehicle program (LEV II), while the federal Tier 2 program regulates both NMOG and NMHC (total non-methane hydrocarbons). The Tier 2 program regulates NMHC under the supplemental exhaust emissions standard for both cars and light trucks based on vehicle weight. These NHMC and NMOG standards measure the total hydrocarbon emissions minus methane, but NMOG contains additional volatile compounds. With the adoption of Tier 3 and LEV III standards, the federal and California programs are parallel, requiring regulation of NMOG. Manufacturers are given flexibility to measure in-use NMHC emissions and calculate equivalent NMOG emissions with an adjustment factor (65 [28] Fed. Reg. [2000]). Evaporative HC emissions are also regulated.

EPA regulates greenhouse gas emissions from light-duty vehicles as well. EPA and the US Department of Transportation (DOT), which regulates fuel economy under its Corporate Average Fuel Economy (CAFE) program, have largely harmonized greenhouse gas and fuel economy standards, especially as they apply to gasoline-powered vehicles. However EPA also includes standards for methane and $N_2O$ emissions, which relate to vehicle emissions control technologies and other GHG emissions from refrigerants in vehicle air-conditioning systems.

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[1] Particulate matter is typically defined by the diameter of the particle. In this analysis, we consider the impacts of PM10 and not specifically PM2.5, which is more damaging. We are in the process of considering how these impacts could be incorporated into the greenercars.org methodology.

Sulfur dioxide ($SO_2$) is not directly regulated for motor vehicles but is incorporated in our rating system based on vehicle fuel economy and fuel sulfur content, both of which are regulated. Starting January 1, 2017, EPA will require a further reduction in the sulfur content of gasoline and diesel fuel. Sulfur in fuel can greatly decrease the effectiveness of aftertreatment catalysts that remove many of the regulated tailpipe emissions (EPA 2014c). We will consider the new gasoline fuel sulfur content standards for the model year 2017 methodology. We do not explicitly estimate emissions of air toxins, though these have a large overlap with regulated emissions.

### i. Criteria Pollutant Emissions

Tailpipe and evaporative emissions of criteria pollutants are regulated for cars and light trucks under both federal and California vehicle emissions programs.

#### TAILPIPE EMISSIONS

The greenercars.org methodology assumes that on average, over the life of a vehicle, regulated criteria pollutants are emitted at the level of the “full useful life” (defined as 120,000 miles) standards to which the vehicle is certified. Vehicle standards are determined both by the federal government as part of the Tier 2 and now the Tier 3 program and by the state of California’s LEV program (Phase II and Phase III). The federal Tier 3 program begins its phase-in for model year (MY) 2017, but many current vehicles are certifying early to the more stringent standards. The phase-in for LEV III standards started in 2015.

Historically, real-world testing often has shown vehicles’ emissions to be substantially in excess of the standards to which they are 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 or low temperatures and use of the air conditioner are not reflected in the bin certification levels. The Supplemental Federal Test Procedure (SFTP) captures some of these “off-cycle” emissions, 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 vehicles’ emissions may exceed the standards to which they are certified is that in some cases emissions increase with time and mileage, and vehicles are driven farther on average than the “full useful life” of 120,000 miles assumed for purposes of emissions standards (DOT 2006).

In light of these considerations, the greenercars.org methodology in prior years estimated real-world average emissions rates in excess of standards, in many cases several times 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 than previously to their respective certification standards. Data on real-world vehicle emissions are limited, however. While emissions rates well in excess of emissions standards undoubtedly occur, either as a result of vehicle testing that fails to capture real-world driving conditions or as a result of process gaming (as evidenced by the Volkswagen “clean” diesel scandal), we did not have a solid basis in MY 2016 on which to assign emissions values higher than the standard or to distinguish among vehicles certified to a given standard, especially given that some of the diesel vehicles tested along with the Volkswagen diesels did indeed meet their standards. We continued to base our ratings on the level of standards to which vehicles are certified until more data become available.

Greenercars.org employs the full useful life standard levels as default values for average per-mile emissions from model year 2012 onward. We scaled emissions levels for LEV II Partial Zero Emission Vehicles (PZEVs), which meet the same tailpipe standards as LEV II Super Ultra Low Emission Vehicles (SULEVs) but must certify to 150,000 miles, to reflect this added durability. Tier 2 Bin 1 and ZEV vehicles are zero-emissions vehicles. The average grams-per-mile standards for all pollutants and for vehicles of each type are shown in Appendix A.

Updated California (LEV III) and federal (Tier 3) tailpipe emissions programs were adopted in 2012 and 2014, respectively, and a number of 2016 vehicles have been certified to these new 150,000-mile lifetime emissions standards under early compliance mechanisms. These programs, to be phased in between 2017 and 2025, will further lower gasoline sulfur levels and reduce emissions of NOx, volatile organic compounds (VOCs), PM, and CO. Both programs regulate the sum of NMOG and NOx emissions rather than the two pollutants separately, which necessitated an update to the methodology for 2016 because the health impacts of the two pollutants differ, so the sum of their emissions levels is not a value that can be used directly in our EDX.

The Tier 3 Regulatory Impact Assessment states that NOx reduction will be easier than VOC reduction for gasoline vehicles, and that it is reasonable to assume that NOx+NMOG emissions will be one-third NOx and two-thirds VOC. EPA further notes that, for diesel vehicles, NMOG emissions are very low, and therefore the NOx fraction will be higher. (EPA 2014c). We adopted the EPA breakdown of NOx versus NMOG emissions for gasoline engines. For diesel engines, we assume that 100% of the NOx+NMOG standard is attributable to NOx emissions.

### EVAPORATIVE EMISSIONS

Evaporative emissions account for a significant portion of the total hydrocarbon inventory (EPA 2014a). Hydrocarbon vapors leak from fuel tanks, lines, and other fuel system components of a vehicle, and there are non-fuel-related evaporative emissions as well. EPA and CARB regulate these evaporative emissions by means of a series of tests that place stationary vehicles in controlled chambers and subject them 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 bin (CARB 2009). PZEV and ZEV vehicles are the exceptions; they are required to have zero evaporative emissions from the fuel system. Vehicles certified to Tier 3 standards (phase-in begins in 2017) will see a 50% reduction of evaporative emissions levels from Tier 2. Tier 3 adds another test procedure for evaporative emissions controls as well as more stringent standards for onboard diagnostic fuel vapor leak detection and evaporative emissions in general. Vehicles that meet the Tier 3 evaporative emissions standard achieve near-zero fuel vapor emissions similar to PZEV and ZEV vehicles (EPA 2014a).

For light-duty gasoline cars and trucks that are not PZEVs or ZEVs, we use the evaporative emissions values provided by ANL's fuel cycle model, GREET 1_2015, which reflect Tier 3 standards. Tier 2 evaporative emissions levels are 50% higher than the numbers provided by GREET 1. PZEVs and ZEVs have no evaporative emissions from the fuel system but do have non-fuel-related evaporative emissions. We assume that PZEV and ZEV evaporative emissions are 30% lower than those of non-PZEV vehicles of the same class, based on the discussion in CARB (2010). According to GREET 1, diesel-fueled vehicles have no fuel-related evaporative emissions, and compressed natural gas (CNG) vehicles have half the emissions of a gasoline vehicle. We assume the non-fuel-related emissions of these vehicles are the same as those of gasoline vehicles. Estimated evaporative emissions rates for all vehicles are shown in Appendix E.

### ii. Greenhouse Gas Emissions

#### CARBON DIOXIDE EMISSIONS

EPA requires manufacturers to measure tailpipe $CO_2$ emissions in order to certify their vehicles under fuel economy and GHG emissions standards. However it has long been acknowledged that the certification test cycles do not adequately represent real-world driving conditions, and that the certification values consequently overestimate vehicles' fuel economy and underestimate $CO_2$ emissions. Therefore EPA uses additional testing to generate more accurate values for purposes of the consumer label that appears on a new car's window. Greenercars.org draws GHG emissions data from this more extensive testing.

***Gasoline, diesel, and CNG vehicles***. To estimate real-world fuel economy and $CO_2$ values for car and light truck labels, EPA requires that manufacturers use a "five cycle" test. This test comprises the following elements: 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. The test results for these five cycles are then used to calculate adjusted (i.e., label) city and highway fuel economy and $CO_2$ values. EPA computes combined $CO_2$ emissions for label purposes as the average of the adjusted city and highway values, with a 55%/45% weighting of city/highway $CO_2$ emissions.

Manufacturers are required to calculate $CO_2$ emissions and fuel economy for select vehicles (known as emissions data vehicles) in their fleet using both the five-cycle and the "derived five-cycle" methodologies (71 [248] Fed. Reg. 77880 [2010]). The derived five-cycle methodology applies a formula to results from the city and highway test cycles, which are used for compliance purposes, to arrive at more realistic fuel economy estimates. The formulas for city and highway derived fuel economy are shown below:

$$(1)\ Derived\ 5\text{–}\ cycle\ city\ fuel\ economy = \frac{1}{0.003259 + \left(\frac{1.1805}{unadjusted\ city\ FE}\right)}$$

$$(2)\ Derived\ 5\text{–}\ cycle\ highway\ fuel\ economy = \frac{1}{0.001376 + \left(\frac{1.3466}{unadjusted\ hwy\ FE}\right)}$$

If there is a significant difference between the fuel economy estimates produced by the two different methods (more than 4% difference for city estimates and 5% difference for highway estimates), then the manufacturer must use full five-cycle testing for all models within that test group (EPA 2006b). If the comparison shows little difference, then the manufacturer may continue to report derived five-cycle data. For these vehicles, greenercars.org uses the derived five-cycle estimates of city and highway fuel economy. We apply a city/highway weighting of 43%/57% to the derived five-cycle data to calculate combined fuel economy.[2]

Greenercars.org adopts EPA's adjusted city and highway results from the five-cycle testing or the derived five-cycle approach, depending on what the manufacturer has used to come up with label $CO_2$ values. The resulting $CO_2$ emissions values are on average at least 25% above the unadjusted (laboratory) values used to certify vehicles under the GHG emissions standards. Greenercars.org uses the 43%/57% city/highway split for combined $CO_2$ emissions.

Under the light-duty GHG standards, vehicles can earn "off cycle" credits for technologies delivering reductions in GHG emissions (and in many cases fuel consumption) in real-world driving that are not captured, or are inadequately captured, on the EPA "two cycle" test used for certification (77 [199] Fed. Reg. 62649 [2012]). These include air-conditioning improvements, engine stop–start systems, solar roof panels, active grille shutters, and other technologies. However model-by-model data on off-cycle credits are not available, so we do not include the benefits of these technologies in rating vehicles for greenercars.org.

***Plug-in vehicles.*** EPA provides kWh-per-mile data over the city and highway test cycles for plug-in vehicles. Just as for vehicles running on other fuels, however, the test values need to be adjusted to better represent real-world driving patterns.

For battery-electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs), manufacturers have the option of using the derived five-cycle method as their primary approach, because not all of the five tests have defined protocols for these vehicles (76 [129] Fed. Reg. 39501 [2011]). For high fuel economy vehicles, equations 1 and 2 above yield severe downward corrections. EVs are among those high fuel economy vehicles: converting an EV's kWh-per-mile values to miles per gallon using the EPA energy conversion of 33,705 kWh per gallon (76 [129] Fed. Reg. 39526 [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. For this high fuel economy value, the downward correction resulting from equations 1 and 2 would be 38% for city fuel economy and 35% for highway fuel economy.

However, for fuel economy labeling purposes, the agencies cap the correction for EVs at 30% (76 [129] Fed. Reg. 39558 [2011]). The agencies declined to apply the full correction factor for these vehicles because the data used to generate the derived five-cycle equations do not include results from any EVs or other high-mpg vehicles, so these corrections are not empirically based. We adopt this practice for greenercars.org as well. Researchers at Argonne National Laboratory also have used the 30% cap on the downward adjustment (Elgowainy et al. 2010). We note, however, that plausible arguments have been made

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[2] Compared to EPA's 55%/45% label weighting, the 43%/57% weighting better captures real-world combined fuel economy and $CO_2$, as discussed in EPA's 2006 labeling rule (71 [248] Fed. Reg. 77904 [2010]).

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 30% shortfall cap in the greenercars.org methodology, our treatment of EVs may be generous in this regard and should be revisited once data are available.

#### OTHER GREENHOUSE GAS EMISSIONS

Tailpipe emissions of methane ($CH_4$) and nitrous oxide ($N_2O$) have been regulated along with carbon dioxide ($CO_2$) since model year 2012. Vehicles' $CH_4$ and $N_2O$ emissions are subject to caps of 0.030 and 0.010 g/mi, respectively. While EPA's GHG certification test results provide some methane and nitrous oxide emissions data, this information is measured only for a selection of test vehicles (EPA 2015). Therefore, we use the EPA emissions caps of 0.030 and 0.010 g/mi for methane and nitrous oxide. Even after adjusting for the higher global warming potential of these GHGs, these pollutants account for less than 1% of total greenhouse gas emissions of late-model gasoline light-duty vehicles (75 [88] Fed. Reg. 25396 [2010]). Emissions assumptions for both methane and nitrous oxide, as well as other GHGs, are shown in appendix table D1.

### iii. Methodology for PHEVs and Other Dual-Fuel Vehicles

For PHEVs, we calculate GHG emissions rates as the sum of emissions from per-mile gasoline consumption and per-mile electricity consumption. Our approach draws on the following EPA data, for both city and highway cycles: gasoline fuel consumption in charge-sustaining (CS) mode, gasoline consumption and electricity consumption in charge-depleting (CD) mode, and utility factor. A utility factor (UF) is the fraction of miles driven on electric power. The utility factors used here are the Society of Automotive Engineers' (SAE) "multi-day individual utility factors" (MDIUFs), not "fleet utility factors," because the former better represent the utility factor that a typical buyer would experience (SAE International 2010).

Given the eight pieces of data listed above, the per-mile consumption rates for PHEVs are derived as follows:

$$kWh\ per\ mile = (0.43\ city\ kWh\ per\ mile) + (0.57\ highway\ kWh\ per\ mile),$$

where

$$city\ kWh\ per\ mile = city\ UF * city\ CD\ kWh\ per\ mile$$

$$highway\ kWh\ per\ mile = highway\ UF * highway\ CD\ kWh\ per\ mile$$

and

$$gallons\ per\ mile = (0.43\ city\ gallons\ per\ mile) + (0.57\ highway\ gallons\ per\ mile)$$

where

$$city\ gallons\ per\ mile =$$
$$city\ UF * city\ CD\ gallons\ per\ mile + (1 - city\ UF) * CS\ gallons\ per\ mile$$
$$highway\ gallons\ per\ mile =$$
$$highway\ UF * highway\ CD\ gallons\ per\ mile + (1 - highway\ UF) * CS\ gallons\ per\ mile$$

The criteria pollutant emissions we assign to PHEVs are the vehicle's EPA-certified emissions levels, weighted by the estimated percentage of miles not operated in all-electric mode. This approach may overstate some PHEVs' criteria emissions, but data are not available to support an approach better tailored to these vehicles. While PHEVs have no emissions when running on the battery alone, they may nonetheless have emissions in CD mode due to blended mode operation. Certification testing of PHEVs is conducted with vehicles operating in CS mode. They are also tested in CD mode to ensure that they continue to meet their certification levels, but they do not have a separate certification level for CD operation.

To estimate the percentage of miles operating in all-electric mode for the above calculation, we look up the MDIUF of the All-Electric Range (AER) for the given vehicle, as listed in EPA's *Fuel Economy Guide* data set. When the AER is listed as an interval rather than a point value, we use the midpoint.

Greenercars.org scores ethanol flex-fuel vehicles as gasoline vehicles, because usage of E85 remains very low in the United States (EIA 2015). A number of bi-fuel CNG and gasoline pickup trucks have appeared on the market in recent years, but to date these have been available for fleet purchase only, so they are not included in the greenercars.org rankings.

### iv. Methodology for Vehicles between 8,500 and 10,000 Lb GVW

While greenercars.org primarily rates light-duty vehicles—i.e., vehicles under 8,500 lb gross vehicle weight (GVW)—it also includes certain vehicles between 8,500 and 10,000 lb GVW. These include heavy SUVs and passenger vans (medium-duty passenger vehicles, or MDPVs) as well as, until recently, some heavy-duty pickup trucks and cargo vans (Class 2b trucks). MDPVs are regulated under the same emissions and fuel economy programs as are light-duty vehicles. Greenercars.org methodology applies unaltered to these vehicles.

Class 2b pickups and vans are now subject to GHG emissions and fuel efficiency standards, but they are covered under the heavy-duty vehicle standards. However Class 2b vehicles are not subject to fuel economy labeling requirements, and as a result they have not been included in EPA's data set to date.

Many Class 2b pickups are variants of light-duty trucks (LDTs) and are frequently used as personal vehicles (80 [133] Fed. Reg. 40138-40765 [2015]). In the past, to estimate the fuel economy of a Class 2b truck that has a light-duty counterpart, we scaled from the corresponding LDT vehicle's fuel economy using mass sensitivity coefficients. However, for the past two years, we have been able to apply this methodology to only a small handful of Class 2b vehicles due to a lack of comparable LDT vehicles. As a result, we have decided for the time being to suspend our evaluation of Class 2b pickups.

## *B. 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 vehicle charging for electricity, for example. The quantity of such upstream emissions associated with a given vehicle is proportional to the fuel consumption of that vehicle.

### i. Gasoline, Diesel, CNG, and Fuel Cell Vehicles

GREET 1 provides grams-per-Btu estimates of upstream emissions for gasoline, diesel, CNG, hydrogen (for fuel cell vehicles), and electricity. We pull emissions factors for gasoline, diesel, CNG, and hydrogen directly from the model for use in the greenercars.org methodology. These factors are given in appendix table D2. We use these numbers together with each vehicle's fuel economy to compute grams-per-mile estimates for these emissions. HC emissions associated with refueling are included as part of these upstream emissions, but emissions that occur once fuel is in a vehicle are included under "Evaporative Emissions," discussed above.

### ii. Plug-In Electric Vehicles

While a pure EV has no tailpipe emissions, there are air emissions associated with producing the electricity to charge it. 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 emissions factors that reflect production and combustion of the fuel, or feedstock, for power generation. Kilowatt-hour-per-mile data for these vehicles are discussed in the "Methodology for PHEVs and Other Dual-Fuel Vehicles" section, above. For grams per kWh, we use combustion and feedstock emissions rates for coal, oil, and natural gas power plants from Argonne National Laboratory's GREET 1_2012 model, factoring in electricity transmission and distribution losses. These rates are detailed in appendix tables D3–D6.

Estimating emissions associated with charging EVs over their lifetime requires projections of emissions from electricity generation in future years. GREET electricity emissions rates for future years do not include all information needed for our methodology, so we use Energy Information Administration (EIA) projections of average emissions rates associated with power generation across all means of generation for the next 24 years (EIA 2015). Projected $CO_2$, NOx, and $SO_2$ in grams per kWh until 2040 are presented in figure 2. For other pollutants (including VOCs, $CH_4$, CO, $N_2O$, and PM10) where no EIA projections are available, we applied the rate of decline of $CO_2$ emissions from EIA. Likewise, feedstock emissions of all pollutants are adjusted using the rate of $CO_2$ decline.

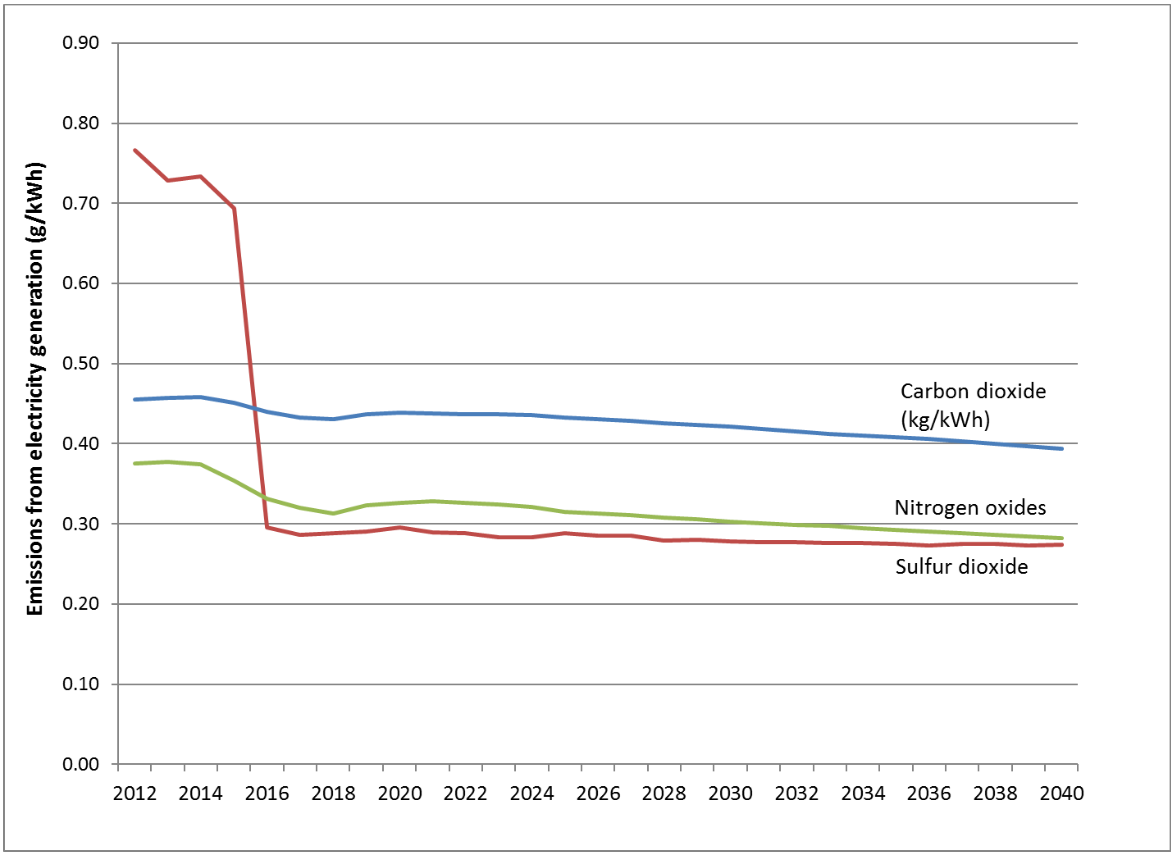

Figure 2. Projected $CO_2$, $SO_2$, and NOx emissions from electricity generation. *Source:* ACEEE calculations based on EIA 2015 and ANL 2012a.

We considered annual vehicle miles traveled (VMT) in calculating lifetime emissions. VMT typically decreases as a vehicle ages, reducing the relative emissions benefits of cleaner power generation in future years. Weighting average VMT per year by vehicle survival rates (Davis, Diegel, and Boundy 2015), we arrived at the distribution of lifetime miles shown in table 2.

Table 2. Average vehicle miles (as a percentage of lifetime travel) over assumed 25-year lifetime

| Year | Vehicle miles as a percentage of lifetime travel | Year | Vehicle miles as a percentage of lifetime travel |
|---|---|---|---|
| 1 | 8.6% | 14 | 3.2% |
| 2 | 8.3% | 15 | 2.8% |
| 3 | 7.9% | 16 | 2.4% |
| 4 | 7.5% | 17 | 2.1% |
| 5 | 7.1% | 18 | 1.8% |
| 6 | 6.8% | 19 | 1.6% |
| 7 | 6.4% | 20 | 1.3% |

| Year | Vehicle miles as a percentage of lifetime travel | Year | Vehicle miles as a percentage of lifetime travel |
|---|---|---|---|
| 8 | 5.9% | 21 | 1.1% |
| 9 | 5.4% | 22 | 0.9% |
| 10 | 4.9% | 23 | 0.8% |
| 11 | 4.4% | 24 | 0.6% |
| 12 | 4.0% | 25 | 0.5% |
| 13 | 3.6% | | |

*Source:* Davis, Diegel, and Boundy 2015

We factored in the annual VMT rate for 25 years to calculate the VMT-weighted emissions rate for all pollutants (see appendix tables D3–D6). Our valuation of health effects treats power plant emissions differently from vehicle emissions, due to differences in exposed populations, as discussed below.

Geographic and temporal differences in electricity generation mix can result in major variations in plug-ins' environmental impacts, depending on where and when they are charged. Our ratings do not reflect such differences in electricity generation mix, but rather use national average emissions rates.[3] Greenercars.org offers a separate calculator for interested users to compute plug-in scores based on their power generation mix (ACEEE 2015).

## C. VEHICLE EMBODIED EMISSIONS

The calculation of embodied GHG and criteria pollutant emissions in the greenercars.org methodology reflects manufacturing, assembly, and recycling/disposal. Argonne National Laboratory's GREET 2 embodied emissions model (ANL 2012b) is the basis for the analysis. GREET 2 breaks down embodied impacts into four categories: (1) vehicle components; (2) batteries; (3) fluids; and (4) vehicle assembly, disposal, and recycling (ADR). The model incorporates elements such as battery manufacturing that differentiate the embodied impacts of more advanced vehicles from those of conventional vehicles. GREET 2 provides life cycle emissions and energy estimates for conventional internal combustion engine (ICE), hybrid-electric, fuel cell, and electric vehicles. The model treats cars, pickup trucks, and SUVs separately.

GREET calculates embodied energy and emissions based on a large number of vehicle-specific inputs, such as vehicle weight, vehicle material composition, fluid composition and weight, and battery size (ANL 2006). As most of these inputs are not available on a model-by-model basis, we use GREET default values for most of them, specifying only vehicle weight and class in the case of ICE vehicles. We also specify battery weight and composition

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[3] In fact, plug-in vehicle sales to date have been heavily concentrated in areas with lower-than-average electric grid emissions, especially California. Hence the EDX may not represent the real-world environmental impact of current plug-in vehicles.

in the case of hybrid-electric, plug-in hybrid, and battery-electric vehicles. For fuel cell vehicles, the weight of the fuel cell stack and associated auxiliaries are also included. Using these few inputs and the formula below, we generate vehicle-specific estimates of greenhouse gas emissions, carbon monoxide, nitrogen oxides, hydrocarbons, and particulate matter emissions from the vehicle life cycle.

$$Total\ embodied\ emissions =$$

$$Y_{s,t} + \ (W_{s,t} * vehicle\ weight) + (B_{s,t} * battery\ weight) + (F_{s,t} * fuel\ cell\ and\ auxiliaries\ weight)$$

where $s$ = emissions species type, $t$ = technology type, $W$ = vehicle weight coefficient, $B$ = battery weight coefficient, $F$ = fuel cell and auxiliaries coefficient, $Y$ = y intercept.

GREET's emissions estimates for each pollutant and vehicle class are linearly related to vehicle weight, battery weight, and fuel cell stack weight. The y-intercepts of some of the linear formulas generated in this way are quite large, indicating that large quantities of certain pollutants associated with embodied impacts 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, more than half of the emissions from assembly, disposal, and recycling are associated with the assembly process, which may in fact be largely independent of vehicle weight. Disposal- and recycling-related emissions, on the other hand, could be expected to be roughly proportional to vehicle weight.

In light of these various considerations, for each pollutant we reduced the intercept by the percentage of the embodied emissions we determined to scale with vehicle weight and pivoted the line around the point defined by the default GREET vehicle weight to pass through the new intercept. The adjusted slopes and intercepts of the linear relationships between vehicle weight and embodied emissions for conventional vehicles are shown in appendix table B1. Our choice of components to scale with weight can be found in appendix table B6.

For hybrid-electric and all-electric vehicles, we input to GREET 2 the size and composition of the battery along with vehicle weight. This year's hybrid offerings include vehicles with nickel metal hydride (Ni-MH) and lithium-ion (Li-ion) battery composition. GREET assumes that both Ni-MH and Li-ion batteries last the lifetime of the vehicle. Appendix tables B2–B4 show the slopes and intercepts of the resulting linear formulas for hybrid and plug-in vehicles. Fuel cell vehicle inputs include vehicle weight, battery size and composition, and the weight of the fuel cell stack and auxiliaries. Table B5 shows the linear formulas for fuel cell vehicles.

Until MY 2016, the greenercars.org methodology assumed that both cars and trucks travel only the "full useful life" of 120,000 miles used for purposes of emissions standards (DOT 2006). However today's vehicles are typically driven substantially farther. Consequently their embodied emissions are lower, on a grams-per-mile basis, than the assumption of 120,000 lifetime miles would indicate.

As part of both the MY 2012–2016 and 2017–2025 rulemakings, EPA and DOT assume that cars travel an average of 195,264 miles and trucks travel 225,865 miles over their lifetimes (EPA and DOT 2010, 2012). These lifetime VMT estimates indicate that (1) vehicles last for more miles than they used to, which does in fact reduce their per-mile impact, and (2) trucks survive longer than cars, both in years and in total miles. However a closer look shows that the agency numbers above are a result of a projection of 2006 VMT figures for cars and light trucks using fuel price and (increasing) driving levels (DOT 2006).

Given the speculative nature of the agency extrapolation and the added consideration that many cars are shipped overseas before the end of their useful lives, we decided to apply a common, rounded lifetime VMT number of 200,000 to cars and trucks for the purpose of evaluating embodied emissions.

## 5. Impact Valuation and Results

To characterize 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 noneconomic judgment that assigns a monetary value to greenhouse gases relative to the economically derived values for conventional air pollutants.

### *A. ENVIRONMENTAL DAMAGE COSTS*

Among the common approaches for estimating environmental externalities are the use of control costs and the use of damage costs. Control costs are based on observations of the costs incurred to reduce pollution, such as the cost of cleanup 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 from 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, 1 gram of PM emitted from a vehicle tailpipe differs substantially from the impact of 1 gram of PM emitted from a power plant, which is likely to be farther away from population centers. Thus, the damage cost value for a given pollutant varies depending on 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 subjects in various locations relative to dispersion of emissions from light-duty motor vehicles, yielding damage cost reduction factors. Delucchi and McCubbin estimated reduction factors for 13 general emissions sources, including fuel combustion in power plants and industrial facilities.

For base damage costs, i.e., 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). We then used the work of Delucchi and McCubbin to assign damage costs to each pollutant when emitted from a refinery or factory (during fuel production or vehicle manufacture) and when emitted from a power plant (during production of electricity used to charge a plug-in vehicle). Reviewing the wide range of factors, we selected a multiplier of 0.1 for the damage cost of pollutants from electric utilities relative to those from vehicles. We selected a multiplier of 0.2 for factories and refineries, which entail higher worker and community exposure than do power plants, on average.

The resulting estimates for major pollutants by location are shown in table 3. These estimates assign a relatively high cost to PM10 and its precursors (particularly $SO_2$ and NOx).

**Table 3. Damage cost estimates for principal air pollutants**

| Marginal cost by location of emissions (2004$/kg) | | | |
|---|---|---|---|
| Pollutant | 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 |
| NOx | 6.24 | 1.25 | 0.62 |
| $SO_2$ | 29.42 | 5.88 | 2.94 |
| PM10 | 50.09 | 10.02 | 5.01 |

[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. *Source:* Delucchi 2004.

Since the average US 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. However the impacts are significant, so we incorporate them in the greenercars.org analysis. 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.

External costs of nuclear power have been extensively investigated for electric sector studies. The greenercars.org methodology currently bases its nuclear damage costs on Rabl and Rabl (2013). Given the relatively safe history of US nuclear operations and the high uncertainty associated with accident estimates, the bulk of these external costs relate to the cost of routine operations and decommissioning. Of the 0.63¢/kWh (2013 dollars) total cost, 0.10¢/kWh is for accidents. We adjust this figure to 2004 dollars to be consistent with our current methodology, which gives us a total external cost of electricity of 0.53¢/kWh. Prorating this estimate by the 20% share of nuclear power in the mix adds 0.11¢/kWh to the overall external cost of electricity, which we estimate for the 2015 model year analysis at 0.75¢/kWh. This value is used to calculate the environmental damage from electric vehicle charging.

A wide range of damage costs have been proposed for GHG emissions. The original greenercars.org methodology simply assumed that GHG emissions from an average vehicle imposed damages equal to those from criteria air pollutant emissions from that vehicle (DeCicco and Thomas 1999b). 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, NOx, VOC, etc.). This established a quasi-damage cost for GHG of $87 per ton of carbon (2004 dollars), or $24 per metric ton $CO_2$-equivalent, which we have kept constant (in real dollars) since that time. By way of comparison, federal agencies used $26 per metric ton $CO_2$ (2010 dollars) as the primary damage cost in the MY 2017–2025 fuel economy and GHG rulemaking (77 (199) Fed. Reg. 62629 (2012)). Thus, the greenercars.org damage cost is close to the agencies' recent estimate.

## *B. SUMMARY OF LIFE CYCLE ESTIMATES*

Starting with an EPA-supplied database, we compiled a database of all new light-duty vehicles on the US market in 2016 and carried out the rating analysis for each configuration of every make and model (1,158 in total). Figure 3 shows the resulting EDX distribution for the overall light-duty fleet, and figure 4 shows the distributions separately for cars (cars and wagons) and light trucks (pickups, vans, and sport utility vehicles).[4] These results are not sales-weighted and so represent the "menu" of vehicles offered to the market, as opposed to the market outcome. The 2016 EDX results range from 0.82¢/mi (an all-electric vehicle) to 3.15¢/mi (a four-wheel-drive, six-liter midsize SUV). The median is 1.74¢/mile.

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[4] This classification does not reflect the shift of two-wheel-drive SUVs under 6,000 lb. GVWR from the truck class to the car class for purposes of fuel economy standards, starting with model year 2011.

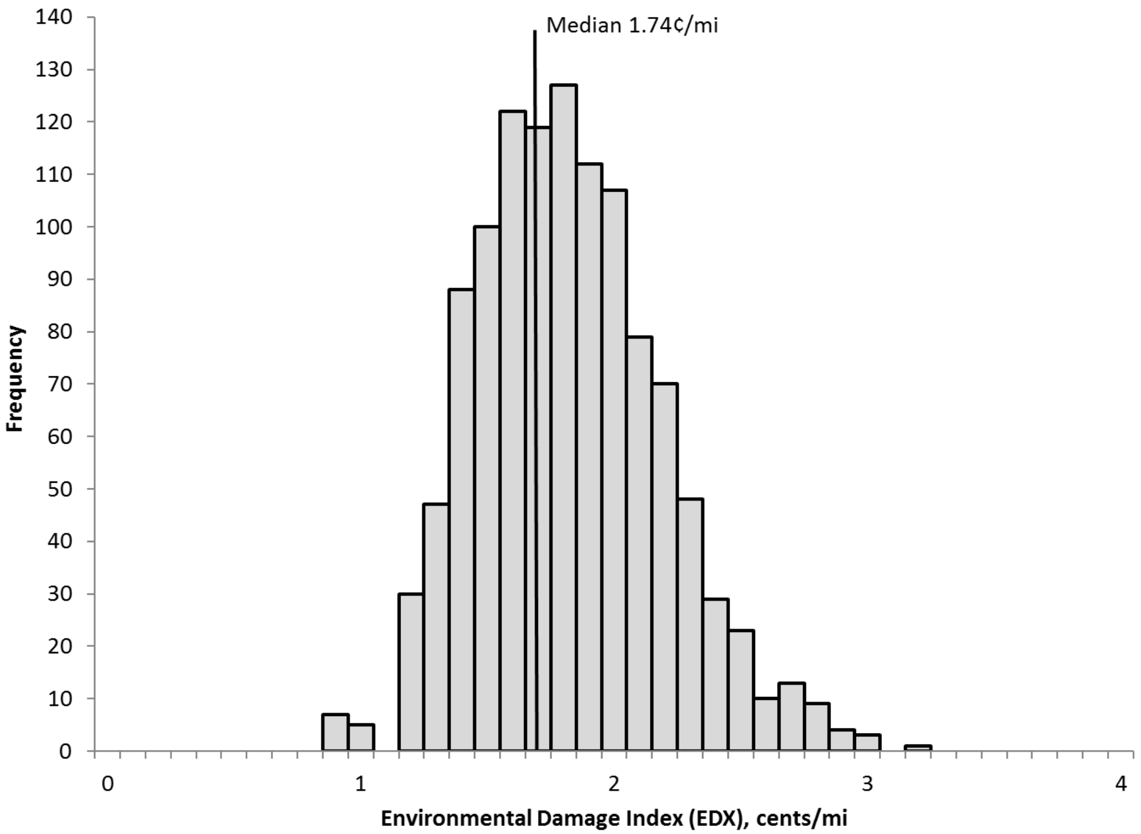

Figure 3. Distribution of Environmental Damage Index (EDX) for MY 2016 for cars and light trucks combined

As shown in figure 4, the median EDX for passenger cars is 1.64¢/mi, while the median for light-duty trucks is 1.95¢/mi. Most light trucks fall into the LDT2 category, which covers light-duty trucks with a laded vehicle weight (curb weight plus 300 lb) of more than 3,750 lb. This model year, the majority of LDT2 vehicle configurations are jointly certified to California LEV II ULEV and federal Tier 2 bin 5, the same standard to which the majority of passenger cars are certified. Note that greenercars.org uses a classification of cars and trucks different from that of EPA and DOT for fuel economy and GHG regulation purposes (see Appendix F for a detailed discussion). In general, vans, pickups, and SUVs are considered trucks for Green Score purposes, and we avoid any classification distinction between four-wheel-drive and two-wheel-drive vehicles, listing these drive train variants together within a vehicle size class.

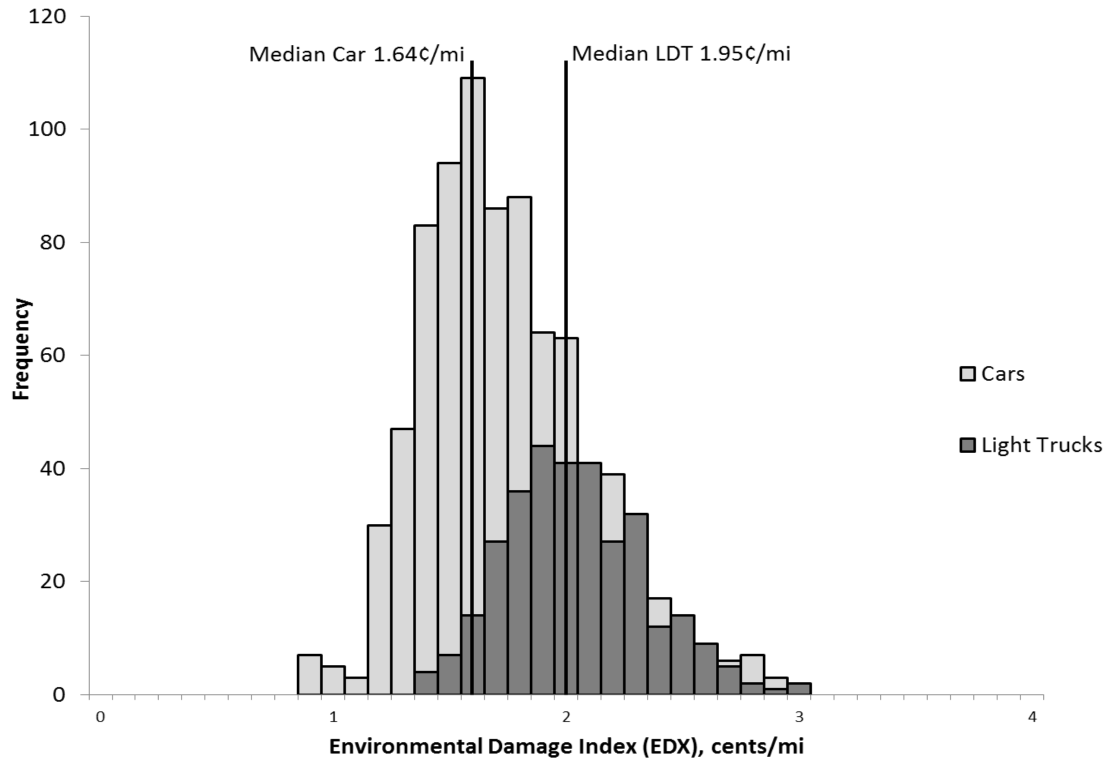

Figure 4. Distribution of Environmental Damage Index (EDX) for MY2016 for cars and light trucks separately

Appendix C details the EDX calculations for an average MY 2016 car and an average MY 2016 light truck. The first three tables itemize health-related criteria emissions impacts for direct vehicle emissions, upstream emissions, and emissions embodied in materials and vehicle assembly and disposal. Lifetime average (g/mi) emissions rates are multiplied by damage costs from table 3 to obtain life cycle cost estimates in cents per mile.

Greenhouse gas emissions calculations are shown in appendix tables C5 and C11. Emissions from each source are summed and then multiplied by the global warming potential (GWP) that represents the radiative forcing of each GHG species compared with that of $CO_2$ (Delucchi 2006). The total lifetime average $CO_2$-equivalent emissions rate (e.g., 492 g/mi for the average car) is then multiplied by the quasi-damage cost chosen 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, on average, 73% of the EDX for the universe of vehicles evaluated in MY 2016.

More detailed breakdowns of the components of the EDX for the average car and the average light truck are shown in table 4.

Table 4. Summary of EDX components for average car and light truck

| Vehicle type | | In-use | Embodied | Fuel cycle |
|---|---|---|---|---|
| | Criteria emissions | | | |
| Car | Cents/mile | 0.13 | 0.21 | 0.13 |
| | % of total EDX | 8% | 13% | 8% |
| Light truck | Cents/mile | 0.13 | 0.23 | 0.15 |
| | % of total EDX | 7% | 12% | 8% |
| | Greenhouse gas emissions | | | |
| Car | Cents/mile | 0.84 | 0.14 | 0.19 |
| | % of total EDX | 44% | 7% | 10% |
| Light truck | Cents/mile | 0.97 | 0.15 | 0.22 |
| | % of total EDX | 51% | 8% | 11% |

Figure 5 shows how the six components of the EDX vary by vehicle technology type and fuel. This figure graphically explains the relative differences in EDX for the vehicle technologies that exist in the marketplace today. Each vehicle technology type is represented by a vehicle with an EDX that equals the average EDX for that technology group. For the plug-in hybrids, however, we chose the most typical plug-in on the market today, since no one vehicle closely matched the average EDX.

For gasoline and diesel vehicles, the single largest component of the EDX is in-use GHGs. For hybrid vehicles, in-use GHG accounts for approximately 50% of the EDX, and embodied impacts play more of a role due the fact that these vehicles are outfitted with larger batteries. EVs and fuel cell vehicles have no in-use emissions at all, so the average EDX for these vehicles is attributable to high upstream GHG and criteria pollution.

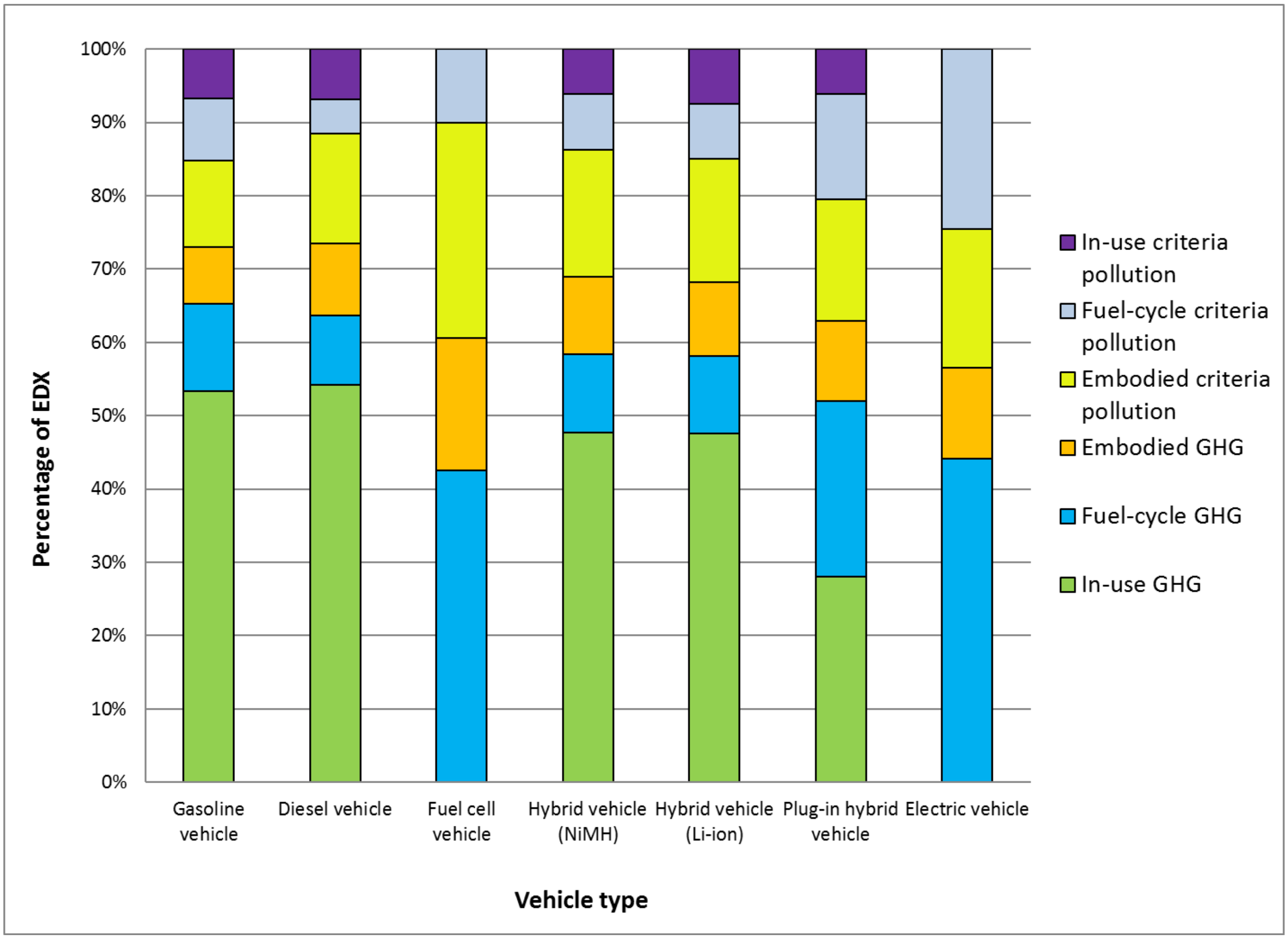

Figure 5. EDX breakdown by vehicle technology

Delucchi and McCubbin (2010) identify a significant range in the value of human health externalities of criteria air pollution from US motor vehicle use. 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. 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. Assuming the average person drives 11,287 miles per year, as estimated by the Federal Highway Administration (FHWA 2015), cost-per-mile values calculated in the greenercars.org ratings analysis indicate that the annual external cost of the average 2016 vehicle is $198 (2004$), which falls into the range estimated by Delucchi and McCubbin.

## *C. 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. To facilitate communication and make it easier to compare vehicles, we derived from the EDX two indicators to convey ratings for greenercars.org. One is a Green Score on a higher-is-better scale of 0 to 100. The other is a rating that compares vehicles within a given size class.

The Green Score allows comparisons 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. The mapping, shown in figure 5, is:

$$Green\ Score = a * \frac{e^{-EDX/c}}{\left(1+\frac{EDX}{c}\right)^{b}}$$

with $a$ = 100, $b$ = 3, and $c$ (gamma) = 6.83¢/mi. We adjust the $c$ value annually to remove the effect of purely methodological changes on Green Scores, making them comparable across model years. Real-world changes in environmental performance are still captured in the change in Green Scores from year to year. To arrive at the $c$ value for 2016, we apply methodological changes for MY 2016 to the MY 2015 data set and calculate the average of the adjusted EDX. We then solve the following equation for $c_{2016}$:

$$\frac{e^{-EDX2015/c2015}}{\left(1+\frac{EDX2015}{c2015}\right)^{b}} = \frac{e^{-EDX2016method/c2016method}}{\left(1+\frac{EDX2016method}{c2016method}\right)^{b}}$$

With this new $c$ value, applying the 2016 methodology leaves the average Green Score for 2015 vehicles unchanged.

A perfect score of 100 is unattainable since it would require an EDX of 0. Using the parameters shown, Green Scores for MY 2016 vehicles range from 20 to 63, with an average of 40, as shown in figure 6.

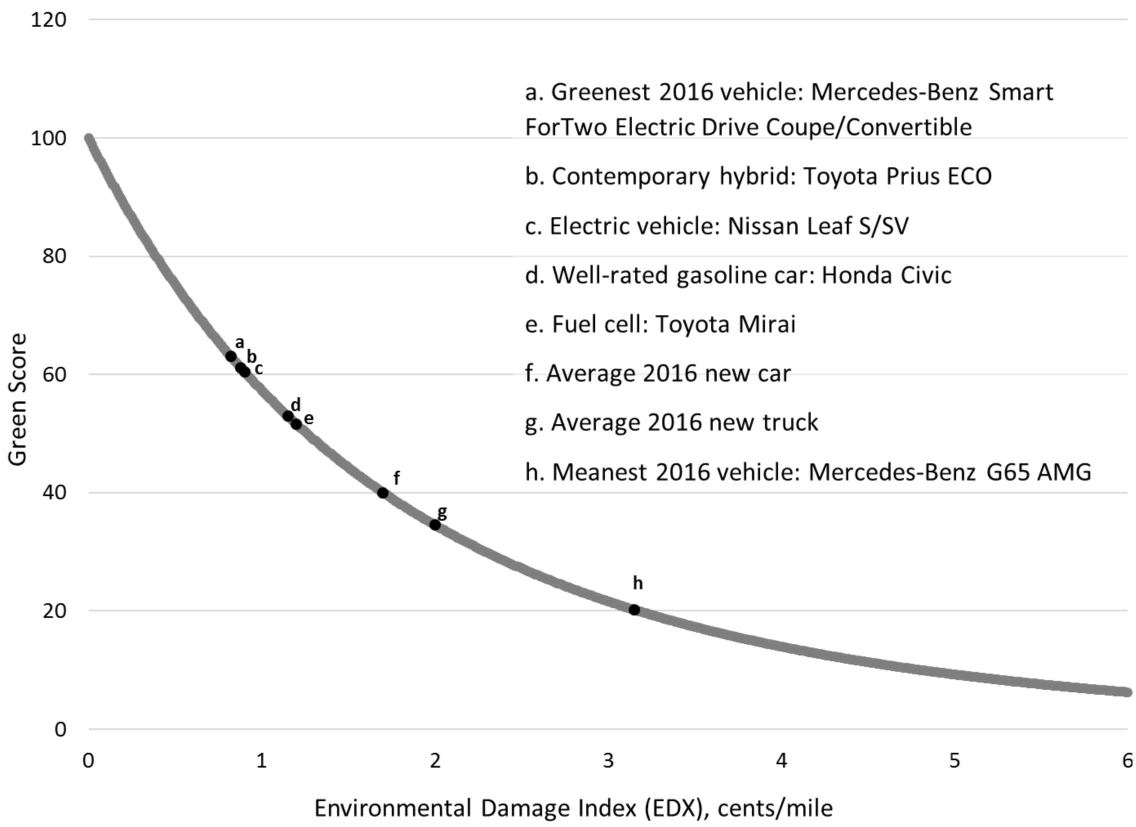

**Figure 6. Green Score vs. EDX with sample 2016 vehicles**

When car shopping, many consumers target a given vehicle class and are unlikely to shop outside that class (for example, to consider a subcompact when looking for a minivan). To facilitate comparisons within classes, we developed the five-tier within-class rating scheme shown in table 5. In assigning within-class ratings, we considered the number of vehicles in each class and natural breaks in the distribution rather than rigidly applying the cut points listed in the table. An additional constraint was that no vehicle that scored worse than the model-year average (a Green Score of 40, corresponding to an EDX of 1.76¢/mi) could obtain a Superior rating. The exact cut points used for each class are provided in appendix table F1.

**Table 5. Percentile guidelines for within-class vehicle ratings**

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

[a] For a Superior rating, a vehicle must also have a Green Score of no less than 40, corresponding to the MY 2016 combined car-truck average EDX of 1.76¢/mi.

## 6. Upcoming Changes and Areas for Future Work

The greenercars.org methodology provides a flexible framework that is refined and updated as new data become available. The parameters and assumptions described in this document reflect those used in the current greenercars.org analysis. Several areas we are considering for further improvement are highlighted below. We look forward to receiving comments regarding these and other methodological issues.

### *A. UPSTREAM ELECTRICITY EMISSIONS*

The greenercars.org methodology currently uses emissions factors from GREET 1_2012 to assess upstream criteria pollutant emissions from electricity generation. Argonne National Laboratory recently released an updated version of the model, GREET 1_2014. Table 6 highlights emissions estimates that changed significantly between the 2012 and 2014 versions of the model and that would have large impacts on the greenercars.org ratings for plug-in vehicles.

**Table 6. Change in electricity combustion and feedstock emissions between GREET 1_2012 and GREET 1_2014**

| | GREET 1_2012 value (g/kWh) | GREET 1_2014 value (g/kWh) | Percentage change |
|---|---|---|---|
| | Combustion | | |
| Coal $SO_X$ | 2.26 | 3.20 | 41.4% |
| Coal PM10 | 0.10 | 0.29 | 189.0% |
| Coal CO | 0.99 | 0.12 | –87.7% |
| | Feedstock | | |
| Coal PM10 | 173.73 | 8.91 | –94.9% |
| Natural gas $CH_4$ | 476.92 | 158.73 | –66.7% |
| Natural gas $N_2O$ | 0.09 | 0.80 | 763.3% |
| Natural gas CO | 7.90 | 23.42 | 196.3% |

The major changes in feedstock and combustion emissions estimates for PM10 would have had the greatest impact on plug-in vehicle emissions. Communications with ANL indicate that changes in coal feedstock estimates arise from the fact that the newer GREET model adopted PM10 and PM2.5 emissions factors recently proposed by EPA for coal surface mining. Likewise, for underground coal mining, emissions factors were updated and were calculated using data from an Australian study that estimated coal particulate matter from an underground mine in Ravensworth (Xstrata 2012).

Applying updated emissions factors based on GREET 1_2014 to model year 2015 electric vehicles resulted in a net average increase in Green Score of almost 5 points. Some electric vehicles saw an increase as high as 6 points. However we do not yet have adequate information to understand whether these major changes in emissions factors reflect real-world conditions. Therefore, for MY 2016, we found it most appropriate to continue with data from GREET 1_2012. We are continuing our efforts to determine whether it is appropriate to incorporate upstream electricity emissions factors from GREET 1_2014.

### *B. PARTICULATE MATTER*

Fine particles are generally a greater threat to health than coarse particles are. Greenercars.org's current treatment of particulate matter focuses on PM10. Other information such as GREET outputs is reported separately for PM2.5, however, and PM2.5 dominates tailpipe PM emissions. We will consider supplementing or replacing PM10 emissions with PM2.5 emissions and applying the appropriate (higher) health damage costs in the calculation of EDX.

### *C. FUEL SULFUR*

Tier 3 fuel sulfur standards take effect in 2017, limiting the annual average gasoline sulfur content to 10 parts per million (ppm), a reduction from the current limit of 30 ppm. The reduction in sulfur content will reduce NOx, VOC, PM, CO, and air toxins from new and existing vehicles by increasing the effectiveness of aftertreatment catalysts (EPA 2014c). We plan to analyze the overall impact of decreased gasoline sulfur content and implement this into the methodology for model year 2017.

### *D. EMISSIONS STANDARDS VS. REAL-WORLD EMISSIONS*

Our current approach of using a vehicle's emissions certification to estimate in-use criteria pollution reflects the lack of up-to-date data on in-use vehicle emissions and how they vary by bin certification, vehicle type, and/or fuel type. EPA's Motor Vehicle Emissions Simulator (MOVES) can be used to generate real-world emissions estimates but does not estimate the certification-bin-specific emissions necessary for the greenercars.org methodology. This topic will be revisited in the future.

## 7. Conclusion

Developing and refining ACEEE's greenercars.org methodology 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 continued progress toward an environmentally sustainable transportation system. We welcome suggestions for improving the greenercars.org ratings in terms of both methodology and presentation.

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# Appendix A. Federal and California Tailpipe Emissions Standards

Table A1. Tier 2 full (useful life) vehicle tailpipe emissions standards for all vehicles (g/mi)

| | CO | NMOG | NOx | PM10 |
|---|---|---|---|---|
| Bin 1 | 0.0 | 0.0 | 0.0 | 0.0 |
| Bin 2 | 2.1 | 0.01 | 0.02 | 0.01 |
| Bin 3 | 2.1 | 0.055 | 0.03 | 0.01 |
| Bin 4 | 2.1 | 0.07 | 0.04 | 0.01 |
| Bin 5 | 4.2 | 0.09 | 0.07 | 0.01 |
| Bin 6 | 4.2 | 0.09 | 0.1 | 0.01 |
| Bin 7 | 4.2 | 0.09 | 0.15 | 0.02 |
| Bin 8 | 4.2 | 0.125 | 0.20 | 0.02 |

*Source:* 65 (28) Fed. Reg. 6734 (2000)

Table A2. Tier 3 full (useful life) vehicle tailpipe emissions standards for all vehicles (g/mi)

| | CO | NMOG + NOx | HC | PM10 |
|---|---|---|---|---|
| Bin 0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Bin 20 | 1.0 | 0.02 | 0.004 | 0.003 |
| Bin 30 | 1.0 | 0.03 | 0.004 | 0.003 |
| Bin 50 | 1.7 | 0.05 | 0.004 | 0.003 |
| Bin 70 | 1.7 | 0.07 | 0.004 | 0.003 |
| Bin 85 | 2.1 | 0.085 | 0.004 | 0.003 |
| Bin 110 | 2.1 | 0.110 | 0.004 | 0.003 |
| Bin 125 | 2.1 | 0.125 | 0.004 | 0.003 |
| Bin 160 | 4.2 | 0.160 | 0.004 | 0.003 |

*Source:* 79 (81) Fed. Reg. 23453–23454 (2014)

**Table A3. LEV II full (useful life) vehicle tailpipe emissions (g/mi) for LDV/LDT/MDPV vehicles**

| | CO | NMOG | NOx | PM10 |
|---|---|---|---|---|
| ZEV | 0 | 0 | 0 | 0 |
| PZEV | 1 | 0.01 | 0.02 | 0.01 |
| SULEV II | 1 | 0.01 | 0.02 | 0.01 |
| ULEV II | 2.1 | 0.055 | 0.07 | 0.01 |
| LEV II | 4.2 | 0.09 | 0.07 | 0.01 |

*Source:* CARB 1999

**Table A4. LEV III full (useful life) vehicle tailpipe emissions (g/mi) for all LDV and LDT <8,500 lb GVM**

| | CO | NMOG+NOx | PM10 |
|---|---|---|---|
| ZEV | 0 | 0 | 0 |
| PZEV | 1.0 | 0.020 | 0.01 |
| SULEV20 | 1.0 | 0.020 | 0.01 |
| SULEV30 | 1.0 | 0.030 | 0.01 |
| ULEV50 | 1.7 | 0.050 | 0.01 |
| ULEV70 | 1.7 | 0.070 | 0.01 |
| ULEV125 | 2.1 | 0.125 | 0.01 |
| LEV160 | 4.2 | 0.160 | 0.01 |

*Source:* CARB 2012

## Appendix B. Evaluation of Embodied Emissions Impacts

Tables B1–B5 show the coefficients of the linear formulas we use to estimate emissions from vehicle manufacturing, assembly, and disposal.

**Table B1. Conventional internal combustion engine vehicles**

| | Pollutant | Intercept (grams per vehicle) | Weight coefficient (grams per lb of vehicle) |
|---|---|---|---|
| Cars | GHGs | 600,136 | 2,356 |
| | PM10 | 361 | 3.45 |
| | NOx | 684 | 2.92 |
| | $SO_x$ | 777 | 8.57 |
| SUVs | GHGs | 855,455 | 2,333 |
| | PM10 | 452 | 3.41 |
| | NOx | 926 | 2.91 |
| | $SO_x$ | 1,225 | 8.28 |
| Pickup trucks | GHGs | 777,073 | 2,283 |
| | PM10 | 400 | 3.43 |
| | NOx | 824 | 2.83 |
| | $SO_x$ | 902 | 8.17 |

**Table B2. Hybrid-electric vehicles (nickel metal hydride batteries)**

| | Pollutant | Intercept (grams per vehicle) | Weight coefficient (grams per lb of vehicle) | Battery weight coefficient (grams per lb of battery) |
|---|---|---|---|---|
| Cars | GHGs | 534,408 | 2,356 | 1,624 |
| | PM10 | 321 | 3.40 | 0.88 |
| | NOx | 574 | 2.91 | 2.34 |
| | $SO_x$ | 639 | 10.02 | 51.31 |
| SUVs | GHGs | 690,833 | 2,355 | 1,633 |
| | PM10 | 347 | 3.41 | 0.88 |
| | NOx | 680 | 2.92 | 2.36 |
| | $SO_x$ | 722 | 9.78 | 51.64 |
| Pickup trucks | GHGs | 690,835 | 2,284 | 1,632 |
| | PM10 | 347 | 3.39 | 0.85 |
| | NOx | 680 | 2.82 | 2.36 |
| | $SO_x$ | 722 | 9.62 | 51.62 |

Table B3. Hybrid-electric vehicles (lithium-ion batteries)

| | Pollutant | Intercept (grams per vehicle) | Weight coefficient (grams per lb of vehicle) | Battery weight coefficient (grams per lb of battery) |
|---|---|---|---|---|
| Cars | GHGs | 534,409 | 2,356 | 693 |
| | PM10 | 321 | 3.40 | 1.74 |
| | NOx | 574 | 2.91 | 1.19 |
| | $SO_x$ | 639 | 10.02 | 6.84 |
| SUVs | GHGs | 690,833 | 2,499 | 700 |
| | PM10 | 347 | 3.53 | 1.73 |
| | NOx | 680 | 3.12 | 1.20 |
| | $SO_x$ | 722 | 10.11 | 7.13 |
| Pickup trucks | GHGs | 534,409 | 2,356 | 693 |
| | PM10 | 321 | 3.40 | 1.74 |
| | NOx | 574 | 2.91 | 1.19 |
| | $SO_x$ | 639 | 10.02 | 6.84 |

Table B4. Electric vehicles (lithium-ion batteries)

| | Pollutant | Intercept (grams per vehicle) | Weight coefficient (grams per lb of vehicle) | Battery weight coefficient (grams per lb of battery) |
|---|---|---|---|---|
| Cars | GHGs | 509,815 | 2,218 | 477 |
| | PM10 | 313 | 3.21 | 1.20 |
| | NOx | 542 | 2.67 | 0.97 |
| | $SO_x$ | 605 | 10.03 | 4.40 |
| SUVs | GHGs | 651,737 | 2,293 | 487 |
| | PM10 | 334 | 3.30 | 1.19 |
| | NOx | 629 | 2.76 | 0.99 |
| | $SO_x$ | 668 | 10.01 | 4.65 |

**Table B5. Fuel cell vehicles (lithium-ion batteries)**

| | Pollutant | Intercept (grams per vehicle) | Weight coefficient (grams per lb of vehicle) | Battery weight coefficient (grams per lb of battery) | Fuel cell stack and auxiliaries coefficient (grams per lb of fuel cell stack) |
|---|---|---|---|---|---|
| Cars | GHGs | 651,737 | 2,133 | 680 | 2,192 |
| | PM10 | 334 | 3.08 | 1.86 | 2.72 |
| | NOx | 629 | 2.55 | 1.19 | 3.05 |
| | $SO_x$ | 668 | 9.03 | 7.55 | 6.01 |
| SUVs | GHGs | 651,737 | 2,140 | 680 | 2,192 |
| | PM10 | 334 | 3.13 | 1.86 | 2.72 |
| | NOx | 629 | 4.68 | 1.19 | 3.05 |
| | $SO_x$ | 668 | 8.88 | 7.55 | 6.01 |

**Table B6. Components of intercept that are assumed to scale with weight**

| | Component of GREET 2.7 intercept | Scales with weight? |
|---|---|---|
| Battery | | Y |
| Fluids | Engine oil | Y |
| | Power-steering fluid | N |
| | Brake fluid | N |
| | Transmission fluid | N |
| | Power train coolant | N |
| | Windshield fluid | N |
| | Adhesives | Y |
| Components | Tires | Y |
| Assembly, disposal, and recycling | Paint production | N |
| | Vehicle painting | N |
| | Vehicle assembly | Y |
| | Vehicle disposal | Y |

# Appendix C. Environmental Damage Index (EDX) Calculations

## *EDX CALCULATION FOR AN AVERAGE MY 2016 GASOLINE CAR*

### Vehicle Attributes

Each year we select the actual light-duty vehicle most closely matching both fuel economy and vehicle weight averages calculated from the model year data set. This year the average car is a 2016 Hyundai Sonata Limited, 2.0L 4-cylinder, automatic transmission, with label fuel economy of 21 city mpg and 31 highway mpg (25.76 combined adjusted mpg) and inertia test weight (ITW) of 4,000 lb. Based on analysis of the MY 2016 passenger car fleet, a joint certification of LEV II ULEV and Tier 2 bin 5 was selected as the most representative emissions standard.

Table C1. Emissions at the vehicle

| Regulated emissions | Emission standard (grams/mile)* | Damage cost ($/kg) | Life cycle cost (cents/mile) |
|---|---|---|---|
| CO | 2.1 | 0.04 | 0.0087 |
| HC | 0.055 | 0.47 | 0.0026 |
| NOx | 0.07 | 6.24 | 0.0437 |
| PM10 | 0.01 | 50.09 | 0.0501 |

* The emissions standards listed are full useful-life standards.

Table C2. Fuel consumption–dependent emissions

| Fuel consumption–dependent emissions | Emissions factor (grams/gallon) | Emissions rate (grams/mile) | Damage cost ($/kg) | Life cycle cost (cents/mile) |
|---|---|---|---|---|
| Evaporative HC | 0.102 | 0.004 | 0.47 | 0.000 |
| $SO_x$ | 0.194 | 0.008 | 29.42 | 0.022 |
| $CH_4$ | 0.03 | 0.001 | --* | -- |
| $N_2O$ | 0.01 | 0.000 | --* | -- |
| $CO_2$ | 8,887 | 345 | --* | -- |

* Greenhouse gases are not assigned a health damage cost; these emissions are incorporated in table C5

Subtotal: Health-related pollution impacts at the vehicle (cents/mile) = 0.128

Table C3. Emissions from the fuel supply cycle

| Fuel-dependent emissions | Emissions factor (grams/gallon) | Emissions rate (grams/mile) | Damage cost ($/kg) | Life cycle cost (cents/mile) |
|---|---|---|---|---|
| CO | 2.29 | 0.09 | 0.008 | 0.000074 |
| HC | 3.4 | 0.13 | 0.094 | 0.001256 |
| NOx | 4.8 | 0.19 | 1.248 | 0.023397 |
| PM10 | 0.39 | 0.02 | 10.02 | 0.015170 |
| $SO_X$ | 4.12 | 0.16 | 5.89 | 0.094130 |
| $CH_4$ | 9.99 | 0.39 | --* | -- |
| $N_2O$ | 0.3 | 0.01 | --* | -- |
| $CO_2$ | 1,662 | 64.5 | --* | -- |

* Greenhouse gases are not assigned a health damage cost; these emissions are incorporated in table C5

Subtotal: Health-related pollution impacts from fuel supply (cents/mile) = 0.134

Table C4. Emissions embodied in the vehicle (materials, assembly, recycling, disposal)

| | Total emissions (grams) | Emissions rate (grams/mi) | Damage cost ($/kg) | Life cycle cost (cents/mile) |
|---|---|---|---|---|
| NOx | 11,698 | 0.12 | 1.25 | 0.009 |
| PM10 | 13,374 | 0.13 | 10.02 | 0.080 |
| $SO_X$ | 33,103 | 0.33 | 5.88 | 0.117 |
| $CO_2$ | 9,486,968 | 94.87 | --* | -- |

* Greenhouse gases are not assigned a health damage cost; these emissions are incorporated in table C5.

Subtotal: Health-related pollution impacts from embodied emissions (cents/mile) = 0.206

Table C5. Greenhouse gas emissions from all sources

| Source | At vehicle (grams/mile) | Fuel cycle (grams/mile) | Embodied (grams/mile) | Global warming potential (GWP) | $CO_2$ equiv. (grams/mile) |
|---|---|---|---|---|---|
| $CO_2$ | 345.03 | 64.53 | 94.87 | 1 | 504.42 |
| HC | 0.06 | 0.13 | | 2 | 0.38 |
| NOx | 0.07 | 0.19 | | 4 | 1.03 |
| CO | 2.10 | 0.09 | | 5 | 10.94 |
| $CH_4$ | 0.001 | 0.39 | | 22 | 8.56 |
| $N_2O$ | 0.000 | 0.01 | | 355 | 4.82 |
| Total* | 356.1 | 79.2 | 94.87 | - | - |

* Sum weighted by GWP

Total $CO_2$-equivalent GHG emissions (grams/mile) = 492.2

Assumed damage cost factor for GHG emissions, per kg $CO_2$-equivalent = 0.0237

Subtotal: GHG impacts (cents/mile) = 1.167

Table C6. Summary of EDX calculation for an average 2016 car

| Environmental impact | Life cycle cost (cents/mile) |
|---|---|
| At-the-vehicle health-related pollution | 0.128 |
| Fuel cycle health-related pollution | 0.134 |
| Embodied health-related pollution | 0.206 |
| **Subtotal** | **0.468** |
| Greenhouse gas impacts | 1.167 |
| **Total EDX** | **1.63** |
| **MY 2016 Green Score** | **41** |

## *EDX CALCULATION FOR AN AVERAGE MY 2016 GASOLINE LIGHT TRUCK*

### Vehicle Attributes

Each year, we select the actual light-duty vehicle most closely matching both fuel economy and vehicle weight averages calculated from the model year data set. This year the average light truck is a 2016 Volvo XC60, 2.5L 5-cylinder, automatic transmission, with label fuel economy of 19 city mpg and 26 highway mpg (22.38 combined adjusted MPG) and inertia test weight (ITW) of 4,500 lb. Based on analysis of the MY 2016 light truck fleet, a joint certification of LEV II ULEV and Tier 2 bin 5 was selected as the most representative emissions standard.

Table C7. Emissions at the vehicle

| Regulated emissions | Emissions standard (grams/mile)[a] | Damage cost ($/kg) | Life cycle cost (cents/mile) |
|---|---|---|---|
| CO | 2.1 | 0.04 | 0.0087 |
| HC | 0.055 | 0.47 | 0.0062 |
| NOx | 0.07 | 6.24 | 0.0437 |
| PM10 | 0.01 | 50.09 | 0.0501 |

[a] The emissions standards listed are full-useful-life standards.

Table C8. Fuel consumption–dependent emissions

| Fuel consumption–dependent emissions | Emissions factor (grams/gallon) | Emissions rate (grams/mile) | Damage cost ($/kg) | Life cycle cost (cents/mile) |
|---|---|---|---|---|
| Evaporative HC | 0.100 | 0.004 | 0.47 | 0.000 |
| $SO_X$ | 0.194 | 0.009 | 29.42 | 0.026 |
| $CH_4$ | 0.03 | 0.001 | --* | |
| $N_2O$ | 0.01 | 0.000 | --* | |
| $CO_2$ | 8,887 | 397 | --* | |

Subtotal: Health-related pollution impacts at the vehicle (cents/mile) = 0.131

Table C9. Emissions from the fuel supply cycle

| Fuel-dependent emissions | Emissions factor (grams/gallon) | Emissions rate (grams/mile) | Damage cost ($/kg) | Life cycle cost (cents/mile) |
|---|---|---|---|---|
| CO | 2.29 | 0.10 | 0.008 | 0.000085 |
| HC | 3.4 | 0.15 | 0.094 | 0.00145 |
| $NO_X$ | 4.8 | 0.22 | 1.25 | 0.0269 |
| PM10 | 0.39 | 0.02 | 10.02 | 0.0175 |
| $SO_X$ | 4.12 | 0.18 | 5.89 | 0.108 |
| $CH_4$ | 9.99 | 0.45 | --* | |
| $N_2O$ | 0.3 | 0.02 | --* | |
| $CO_2$ | 1,662 | 74.3 | --* | |

* Greenhouse gases are not assigned a health damage cost; these emissions are incorporated in table C11.

Subtotal: Health-related pollution impacts from fuel supply (cents/mile) = 0.154

Table C10. Emissions embodied in the vehicle (materials, assembly, recycling, disposal)

| | Total emissions (grams) | Emissions rate (grams/mile) | Damage cost ($/kg) | Life cycle cost (cents/mile) |
|---|---|---|---|---|
| $NO_X$ | 13,358 | 0.13 | 1.25 | 0.010 |
| PM10 | 15,020 | 0.15 | 10.02 | 0.090 |
| $SO_X$ | 36,597 | 0.37 | 5.88 | 0.129 |
| $CO_2$ | 10,822,031 | 108.22 | --* | |

* Greenhouse gases are not assigned a health damage cost; these emissions are incorporated in table C11.

Subtotal: Health-related pollution impacts from embodied emissions (cents/mile) = 0.230

Table C11. Greenhouse gas emissions from all sources

| Source | At vehicle (grams/mile) | Fuel cycle (grams/mile) | Embodied (grams/mile) | Global warming potential (GWP) | $CO_2$ equiv. (grams/mile) |
|---|---|---|---|---|---|
| $CO_2$ | 397.16 | 74.275 | 108.22 | 1 | 579.65 |
| HC | 0.06 | 0.154 | | 2 | 0.42 |
| NOx | 0.07 | 0.216 | | 4 | 1.14 |
| CO | 2.10 | 0.102 | | 5 | 11.01 |
| $CH_4$ | 0.001 | 0.446 | | 22 | 9.85 |
| $N_2O$ | 0.000 | 0.015 | | 355 | 5.55 |
| Total* | 408.2 | 91.18 | 108.22 | - | - |

* Sum weighted by GWP

Total $CO_2$-equivalent GHG emissions (grams/mile) = 564.3

Assumed damage cost factor for GHG emissions, per kg $CO_2$-equivalent = 0.0237

Subtotal: GHG impacts (cents/mile) = 1.339

Table C12. Summary of EDX calculation for an average 2016 light truck

| Environmental Impact | Life cycle cost (cents/mile) |
|---|---|
| At-the-vehicle health-related pollution | 0.131 |
| Fuel cycle health-related pollution | 0.154 |
| Embodied health-related pollution | 0.230 |
| **Subtotal** | **0.515** |
| Greenhouse gas impacts | 1.339 |
| **Total EDX** | **1.85** |
| **MY 2016 Green Score** | **37** |

# Appendix D. Fuel Consumption–Dependent Emissions Factors

## *GASOLINE, DIESEL, CNG, AND FUEL CELL VEHICLES*

Table D1. Vehicle in-use emissions factors

| Pollutant | Gasoline (grams/gallon) | Diesel (grams/gallon) | CNG (grams/gasoline gallon equivalent) |
|---|---|---|---|
| $SO_x$ | 0.19 | 0.12 | 0.03 |
| $CO_2$ | 8,887 | 10,180 | 6,677 |

*Source:* Delucchi 2006, EPA 2012

Table D2. Upstream emissions from fuel production, distribution, and vehicle refueling

| Pollutant | Gasoline (grams/gallon) | Diesel (grams/gallon) | CNG (grams/gasoline gallon equivalent) | Fuel cell (grams/gasoline gallon equivalent) |
|---|---|---|---|---|
| HC | 3.44 | 0.93 | 1.28 | 2.15 |
| $CH_4$ | 9.99 | 9.44 | 33.76 | 47.63 |
| CO | 2.29 | 1.68 | 4.05 | 7.23 |
| $N_2O$ | 0.34 | 0.03 | 0.19 | 0.28 |
| NOx | 4.83 | 3.74 | 5.20 | 10.53 |
| $SO_x$ | 4.12 | 2.44 | 2.16 | 7.94 |
| PM10 | 0.39 | 0.25 | 0.12 | 1.87 |
| $CO_2$ (w/C in VOC & CO) | 1,660 | 1,590 | 1,210 | 12,904 |

*Source:* ANL 2015

## *EMISSIONS FACTORS FOR ELECTRIC VEHICLE RECHARGING*

Table D3. Generation mix, generation efficiency, and distribution efficiency assumptions for US electricity generation in 2012

| | Coal | Oil | Natural gas boiler | Natural gas turbine | Nuclear | Renewable | Others | Average net efficiency |
|---|---|---|---|---|---|---|---|---|
| Generation mix | 46.4% | 1.0% | 3.1% | 19.8% | 20.3% | 9.2% | 0.2% | - |
| Generation efficiency | 34.5% | 32.8% | 31.9% | 42.0% | 32.6% | 100.0% | - | - |
| Distribution efficiency | 93.5% | 93.5% | 93.5% | 93.5% | 93.5% | 93.5% | 93.5% | 31.1% |

*Source:* ANL 2012

Table D4. Emissions rates (grams/MBtu input)

| | Coal | Oil | NG boiler | NG turbine |
|---|---|---|---|---|
| NMOG | 1.14 | 2.02 | 1.56 | 1 |
| $CH_4$ | 1.20 | 0.91 | 1.1 | 4.26 |
| CO | 100 | 15.76 | 16.42 | 24 |
| $N_2O$ | 1.06 | 0.36 | 1.1 | 1.5 |
| NOx | 105.7 | 85 | 57.61 | 113 |
| $SO_x$ | 228.65 | 202.58 | 0.27 | 0.27 |
| PM10 | 10 | 16 | 3.21 | 3.1 |
| $CO_2$ (kg/MBtu) | 99.84 | 85.05 | 59.38 | 59.36 |

*Source:* ANL 2012

Table D5. Emissions per unit of delivered power (grams/MBtu)

| | Coal | Oil | Natural gas boiler | Natural gas turbine | National average | VMT-adjusted average g/kWh |
|---|---|---|---|---|---|---|
| NMOG | 27.19 | 17.15 | 24.51 | 17.20 | 16.95 | 0.0560 |
| $CH_4$ | 463.63 | 332.01 | 1602.67 | 1224.95 | 510.72 | 1.6208 |
| CO | 318.03 | 65.67 | 81.55 | 81.22 | 166.83 | 0.4928 |
| $N_2O$ | 3.38 | 1.32 | 4.00 | 4.06 | 2.51 | 0.0070 |
| NOx | 367.28 | 344.76 | 269.47 | 345.62 | 250.64 | 0.5971 |
| $SO_x$ | 731.12 | 691.88 | 40.15 | 30.49 | 353.44 | 0.5757 |
| PM10 | 569.59 | 59.26 | 13.62 | 10.07 | 267.30 | 0.8439 |
| $CO_2$ (kg/MBtu) | 314.46 | 289.64 | 216.79 | 164.56 | 188.12 | 548.42 |

*Source:* ACEEE calculations based on data from ANL 2012

Table D6. Nuclear power externality cost

| Factor | Value |
|---|---|
| Damage cost (¢/kWh) | 0.61 |
| Generation share | 20.3% |
| Cost (¢/kWh) | 0.12 |
| Non-nuclear electricity cost (¢/kWh) | 0.63 |
| Overall external electricity cost (¢/kWh) | 0.75 |

*Source:* ACEEE calculations based on data from ANL 2012

# Appendix E. Evaporative Emissions

Table E1. Evaporative emissions rates by vehicle type (grams/mile), Tier 2/LEV II vehicles

| Vehicle type | LDV | LLDT | HLDT |
|---|---|---|---|
| Gasoline (non-PZEV) | 0.102 | 0.100 | 0.107 |
| PZEV, ZEV, diesel | 0.071 | 0.070 | 0.075 |
| CNG | 0.087 | 0.085 | n/a |

*Source:* ACEEE, based on ANL 2015

Table E2. Evaporative emissions rates by vehicle type (grams/mile), Tier 3/LEV III vehicles

| Vehicle type | LDV | LLDT | HLDT |
|---|---|---|---|
| Gasoline (non-PZEV) | 0.070 | 0.074 | 0.092 |
| PZEV, ZEV, diesel | 0.049 | 0.052 | 0.064 |
| CNG | 0.060 | 0.063 | n/a |

*Source:* ACEEE, based on ANL 2015

## Appendix F. Vehicle Inclusion and Classification

EPA's database of fuel economy data serves as the foundation for the vehicles ACEEE scores and classifies in greenercars.org. ACEEE provides ratings only for vehicles offered for general sale by established automakers that have a mass-production track record. Concept vehicles, prototypes, and premarket test products not yet offered for general sale are not listed; neither are aftermarket devices or conversion vehicles, or other vehicles not certified under US safety and emissions regulatory programs. Makes and models not included in the applicable government certification databases at the time of scoring may be omitted from our ratings.

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 parameters can result in seemingly arbitrary class distinctions among vehicles that fall near the boundaries. Moreover, the market is continually evolving. A notable class that is important today, minivans, did not even exist 40 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 wagons, minivans, and sport utilities can be quite fuzzy, due to the growing share of crossover vehicles on the market. Because crossover vehicles do not fit exactly into the designated greenercars.org 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 by DOE and EPA in the annual *Fuel Economy Guide* (DOE 2016; EPA 2014c). It defines car classes on the basis of interior volume, with a body style distinction separating wagons from coupes and sedans. It also defines light truck classes on the basis of 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 cutoff for each class as specified in the *Fuel Economy Guide*. We combine Minicompacts and Subcompacts into a single class that we term Subcompact Cars. We combine Midsize Station Wagons and Large Station Wagons into a single class that 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 and vans.* We use the DOE and EPA *Fuel Economy Guide* size classes for pickups and vans. Vehicle size classes are based on gross vehicle weight rating (GVWR) for trucks, vans, and SUVs (DOE 2016). Pickup trucks classified as Small or Standard in the *Fuel Economy*

*Guide* are reclassified as Compact or Standard, respectively. Vans are classified in the *Fuel Economy Guide* as minivan, passenger, or cargo vans. We carry over the minivan classification to greenercars.org. Passenger and cargo vans share platforms and as such are classified together as Large Vans.

*Sport utility vehicles.* Because the SUV classification is diverse, we use a classification scheme representative of market segments. For example, we distinguish between vehicles such as the Ford Escape and the GMC Yukon. 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 Ford Explorer 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 four-wheel drive and two-wheel drive, listing these drivetrain variants together within a given utility vehicle size class.

## DISTRIBUTIONS OF EDX BY VEHICLE CLASS

The distributions of EDX for cars, light trucks, and light-duty vehicles overall in MY 2016 are given in figures 3 and 4. Appendix table F1 identifies the EDX cut points used to determine the symbolic within-class ratings assigned to vehicles in greenercars.org. A vehicle is assigned a given class rating if its environmental damage index (EDX) is less than the cut point for the rating and, for a Superior rating, if its Green Score is no less than the overall 2016 average of 40 (corresponding to the MY 2016 combined car–truck average EDX of 1.76¢/mi).

**Table F1. Cut points used to determine class ratings for model year 2015 vehicles (cents/mile)**

| | Superior | Above average | Average | Below average | Inferior |
|---|---|---|---|---|---|
| Percentile guideline | 95% + | 80%–95% | 35%–80% | 15%–35% | 0–15% |
| Two-seaters | 1.15 | 1.60 | 1.93 | 2.23 | >2.23 |
| Subcompact cars | 1.12 | 1.33 | 1.77 | 2.01 | >2.01 |
| Compact cars | 1.16 | 1.34 | 1.60 | 1.85 | >1.85 |
| Midsize cars | 1.17 | 1.31 | 1.65 | 1.99 | >1.99 |
| Large cars | 1.37 | 1.69 | 1.99 | 2.17 | >2.17 |
| Small wagons | 1.15 | 1.36 | 1.55 | 1.74 | >1.74 |
| Midsize wagons | 1.11 | 1.49 | 1.86 | 2.11 | >2.11 |
| Compact pickups | 1.69 | 1.83 | 1.98 | 2.09 | >2.09 |
| Standard pickups | 1.80 | 1.97 | 2.18 | 2.35 | >2.35 |
| Compact SUVs | 1.34 | 1.47 | 1.68 | 1.83 | >1.83 |
| Midsize SUVs | 1.55 | 1.74 | 1.98 | 2.15 | >2.15 |
| Large SUVs | 1.62 | 2.18 | 2.35 | 2.46 | >2.46 |
| Minivans | — | 1.90 | 1.94 | 1.95 | >1.95 |
| Large vans | 1.60 | 1.65 | 1.85 | 2.69 | >2.69 |

## Appendix G: Summary of Methodology Changes Since 2011

A number of modifications to our environmental rating methodology have been made since the publication of the last methodology report for ACEEE's greenercars.org (Vaidyanathan and Langer 2011). Although the life cycle assessment principles underlying the greenercars.org methodology have remained constant between 2011 and 2016, several components were updated to take into account new research, models, and technologies.

### *FULL VEHICLE-LIFE EMISSIONS STANDARDS*

For the 2011 methodology, we used 50,000-mile standards to represent average lifetime emissions for NOx, 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), starting in 2013 we used "full useful life" (120,000 miles) standards instead as per-mile emissions rates. The full-life standards are 20 to 40% higher than the 50,000-mile standards, so using these emissions rates increases the contribution of in-use criteria emissions to the EDX, though only modestly.

### *EVAPORATIVE EMISSIONS*

Previous editions of greenercars.org ratings relied on EPA's MOBILE model to estimate evaporative emissions. However we stopped using the MOBILE model in 2010, and in 2011 the ratings methodology did not account for evaporative emissions.

In 2012, we began using ANL's GREET 1 model to estimate evaporative emissions. GREET 1 provides values for LDV, LLDT, and HLDT gasoline vehicles, which are listed in Appendix E. For Class 2b vehicles (MDPVs and heavy-duty pickups and vans), we adopt a value of 0.085 g/mi, slightly higher than the HLDT rate, reflecting the slightly higher standard for Diurnal + Hot Soak emissions from these vehicles. We apply these emissions rates to all gasoline vehicles other than PZEVs and ZEVs. PZEVs and ZEVs have no evaporative emissions from the fuel system but do have non-fuel-related evaporative emissions. We assume that PZEV and ZEV evaporative emissions are 30% lower than those of non-PZEV vehicles of the same type.

According to GREET 1, diesel-fueled vehicles have no evaporative emissions, and CNG vehicles have half the emissions of a gasoline vehicle. However this would only apply to fuel-related emissions; we assume the non-fuel-related emissions of these vehicles are the same as those of gasoline vehicles.

The 2015 update of GREET 1 provides values for evaporative emissions that are substantially lower than the values in earlier versions. We do not have information explaining these changes, as documentation had not yet been released at the time we published our 2016 ratings. We assume that the reductions in evaporative emissions shown in the 2015 update reflect the adoption of Tier 3 and LEV III standards. Based on that, we used evaporative emissions rates from the 2015 update of GREET 1 for the 2016 model year for Tier 3 vehicles and emissions rates from the 2012 version of GREET 1 for Tier 2 vehicles.

### *EMBODIED EMISSIONS*

Greenercars.org calculates embodied GHG and criteria pollutant emissions using Argonne National Laboratory's GREET 2 model. The 2011 methodology adjusted the linear formulas shown in Appendix B by cutting the y-intercepts in half to account for the fact that some of these emissions should in fact scale by weight. In 2013, we looked in greater detail at the breakdown of the intercepts derived from GREET. We broke down each of the four emissions categories (components, fluids, batteries, and ADR) into subcategories and then divided them into two groups based on whether or not they ought largely to scale with overall vehicle weight. This breakdown can be found in appendix table B6.

ANL issued an updated version of GREET in 2014, but we did not update the greenercars.org methodology to reflect these changes because the GREET 2 vehicle-cycle model incorporates electricity generation emissions updates from GREET 1 for electricity use in the manufacturing process that we were unable to explain. Another update, released in 2015, generates embodied emissions estimates similar to the 2014 model. Using emissions estimates from GREET 2_2015 would have greatly affected our calculations of embodied emissions, but model documentation is not sufficient for us to fully understand these changes. Consequently we continue to use GREET 2_2012 for our estimation of embodied pollutants, and we will address this issue in the future.

### *BATTERY REPLACEMENT ASSUMPTIONS FOR HYBRID AND ELECTRIC VEHICLES*

The 2011 greenercars.org methodology assumed that hybrid-electric vehicles with nickel metal hydride batteries (Ni-MH) are replaced once during a vehicle's lifetime, which was GREET's default assumption. ANL has since updated its embodied model, GREET 2, to incorporate the assumption that nickel metal hydride batteries last the lifetime of the vehicle. As a result, the greenercars.org model has adopted this assumption in its estimation of battery-related emissions impacts.

### *PHEVS AND BLENDED MODE OPERATION*

The first plug-in hybrid rated by greenercars.org was an extended-range EV (EREV) appearing in model year 2011. We used the manufacturer's claim of all-electric range and the Society of Automotive Engineers' fleet utility factor tables, together with EPA data on fuel economy in electric and gasoline operation to calculate full fuel cycle GHG emissions for the vehicle. This approach had shortcomings, including the unofficial source of the range value and the use of fleet utility factors. Our approach from 2012 onward is highlighted in section 4a (iii) in the report.

### *FUEL CELL VEHICLES*

Model year 2015 marked the first year that greenercars.org evaluated fuel cell vehicles (FCVs) as part of the ratings. The model year 2015 Hyundai Tucson FCV was introduced in very limited quantities in Southern California. We used the following methodology for estimating life cycle emissions for fuel cell vehicles.

As with EVs, fuel cell vehicles do not generate in-use GHG and criteria emissions. The vehicle's Green Score is determined first by the upstream impacts associated with the production of hydrogen used to power the vehicle and the emissions from the manufacturing and assembly of the vehicle, the fuel cell stack, and its battery, which are derived from GREET 1 and shown in appendix table D2. We use these factors together with a vehicle's fuel economy to compute grams per mile estimates for these emissions.

The rest of the Green Score for a fuel cell vehicle is determined by manufacturing impacts. Like other vehicle technologies, FCVs' manufacturing emissions (assembly, disposal, and recycling) are determined using results from the GREET 2_2012 model. However, unlike the other vehicle technologies, fuel cell emissions estimates rely on three parameters: vehicle weight, battery weight, and fuel cell and auxiliary system weight.

### *UPSTREAM EMISSIONS FOR GASOLINE, DIESEL, AND CNG VEHICLES*

The 2011 methodology evaluated upstream emissions associated with gasoline, diesel, and CNG vehicles using estimates from the Delucchi Lifecycle Emissions Model (LEM) (Delucchi 2006). These fuel-specific factors address the pollution associated with the extraction, refining, and transporting of fuels from the wellhead to the fuel pump. In 2012, greenercars.org incorporated new upstream methane values from the GREET 1 model to account for increased upstream methane leakage and fugitive emissions that can significantly increase life cycle emissions of CNG as a fuel (Burnham et al. 2011). For model year 2013, in order to be able to track changes in fuel-related policies and practices over time, we switched to GREET for other upstream emissions as well, because GREET is regularly updated.

It should be noted that the overall upstream GHG emissions factors for gasoline and diesel fuels from the GREET model are lower than in Delucchi's LEM, while the GHG emissions factor for CNG is slightly higher. However we found that each of the GHG emissions components in GREET (carbon dioxide (with carbon in VOC and CO), methane, and nitrous oxide) is significantly lower than in the greenercars.org 2012 methodology for all three fuels. This discrepancy is the result of the different global warming potential (GWP) values used by GREET and Delucchi. GREET uses IPCC global warming potential values (Solomon et al. 2007), while the Delucchi LEM uses $CO_2$ equivalency factors that convert the mass of all non-$CO_2$ gases into $CO_2$ (Delucchi, 2005). We continued to use global warming potential factors from Delucchi for the 2013 methodology onward, as the IPCC factors assume that CO, HC, and NOx have no impact on climate. Upstream emissions factors for all fuels are shown in appendix table D2.

ANL issued an update to GREET 1 in 2015, and while we chose not to use this update for upstream emissions factors for electricity as discussed above, we did use the updated numbers for gasoline, diesel, and natural gas vehicles.

### *FORECAST UPSTREAM ELECTRICITY-RELATED EMISSIONS*

For purposes of determining upstream electricity-related emissions, the 2011 methodology relied on data from Delucchi's LEM and was based on the national average emissions profile of electricity over the lifetime of a vehicle. Beginning with the 2014 greenercars.org methodology, we switched to the GREET model, which is regularly updated. However, given the issues outlined earlier in the report regarding electricity feedstock and combustion emissions, we continued to use the 2012 GREET model to estimate upstream electricity emissions rather than using ANL's updates. Additionally, for 2015, we identified two errors in our electricity emissions factors for the 2014 model year, which we corrected for the 2015 ratings. The two errors were: (1) a misstatement of the distribution of NG electricity generation types, which resulted in overstated emissions from NG electricity generation; and (2) a computational error that had varying results on the emissions rates.

### *NUCLEAR DAMAGE COSTS*

Due to the relative safety of nuclear operations in the United States, until recently we considered only the external cost of routine operations and decommissioning in our estimate of nuclear-related impacts. However the earthquake-induced failure of Japan's Fukushima Daiichi plant in 2011 called for a reevaluation of the external costs of nuclear electricity generation.

Starting with model year 2015 ratings, we incorporated accident-related external costs into the overall environmental damage costs associated with the nuclear fuel cycle and referenced more recent data for our consideration of other costs. Our updated methodology uses the findings from Rabl and Rabl (2013), which provides low, central, and high estimates of the external costs of operation, waste management, and accidents of nuclear power. Central external cost estimates are 0.27¢/kWh for normal operations, 0.26 ¢/kWh for waste management, and a range of estimates for accidents. The accident portion was calculated using historical data of nuclear catastrophic accidents at Chernobyl and Fukushima. Cost calculations and assumptions in the report are transparent and based on real damages from both events. Important cost elements include cost of lost reactors, cost of power, fatal cancers, lost agricultural production, displaced populations, and cost of cleanup.

Since we assume that nuclear energy production in the United States is relatively safe, we chose the low tendency calculation as most appropriate for estimating the accident costs of a nuclear accident. For all other costs we used numbers from the central tendency scenario. This selection was also based on the assumption that the safety of nuclear reactors will continue to improve substantially.

### *VMT CHANGES FOR EMBODIED EMISSIONS*

ACEEE's methodology for calculating embodied emissions previously assumed that both cars and trucks travel 120,000 miles over their lifetime. For the 2016 methodology, we use a lifetime VMT of 200,000 for both cars and trucks. Using this higher VMT value will decrease the embodied emissions' contribution to the EDX, because total embodied emissions will remain constant while mileage increases, decreasing the emissions per mile.

### *TIER 3/LEV III EMISSIONS STANDARDS*

The LEV III and Tier 3 passenger vehicle emissions standards regulate the sum of NMOG and NOx rather than the individual pollutants. The first LEV III-certified vehicles appeared in MY 2014, and Tier 3-certified vehicles now appear in the 2016 model year. For MY 2014, we developed an interim methodology to address the transition to the combined NOx +NMOG standard in LEV III and Tier 3. The interim methodology determined NOx and NMOG emissions for each level of the new standards by using the proportion of NOx to NMOG from the corresponding LEV II certification emissions levels (e.g., LEV III LEV160 is equivalent to LEV II LEV).

The Tier 3 Regulatory Impact Assessment (EPA 2014c) states that it is reasonable to assume that NOx +NMOG emissions will be 1/3 NOx and 2/3 VOC, indicating that our interim approach since MY 2014 was conservative for gasoline engines. EPA notes that NMOG emissions are very low for diesel engines, therefore the NOx fraction will be higher (EPA 2014c). Based on this information, we have adopted the EPA breakdown of NOx and NMOG emissions for gasoline engines. For diesel engines, we assume that 100% of the NOx +NMOG emissions are NOx.

### *CLASS 2B VEHICLES*

Beginning in model year 2014, Class 2b pickups and vans were subject to GHG emissions standards and, optionally, to fuel consumption standards. This new program should enable us to rate these vehicles. However the EPA data we use as the basis for our rankings still do not include fuel economy values for 2b pickups and vans. In the past, we were able to estimate the fuel economy of a Class 2b truck that has a light-duty counterpart by scaling from the corresponding LDT vehicle’s fuel economy using mass sensitivity coefficients. In the past few years, we have been able to apply this methodology to only a small number of Class 2b vehicles, due to a lack of comparable LDT vehicles. We are suspending our evaluation of Class 2b vehicles for the 2016 model year. We continue to evaluate MDPVs, for which we receive full fuel economy information from EPA.