Rating the Environmental Impacts of Motor Vehicles: The *Green Guide to Cars and Trucks* Methodology, 1999 Edition

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The *Green Guide to Cars and Trucks* is a consumer-oriented publication which provides comprehensive environmental ratings for cars, vans, pickups and sport utility vehicles, enabling consumers to comparison shop with the environment in mind. Each model is given a Green Score that accounts for both health-damaging air pollutants and climate-threatening greenhouse gas emissions. This technical report documents the methodology used to develop the ratings published in the *Green Guide to Cars and Trucks: Model Year 1999.*

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ABSTRACT

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

The environmental rating methodology for the *Green Guide to Cars and Trucks* is based on principles of life-cycle assessment and environmental economics. The method is designed to be applicable given the limitations of data available by make and model in the U.S. market. The approach combines the impacts of traditionally regulated (criteria) pollutants with those of greenhouse gas emissions, covering both the vehicle life cycle and the fuel cycle, using a mass-based characterization of vehicle manufacturing impacts. This report covers the data issues, key assumptions, and analysis methods used to develop ACEEE's vehicle ratings. It summarizes the application of the methodology to the 1999 model year, highlighting results for major classes and technology types, and identifies research needs for updating and refining the methodology.

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INTRODUCTION

Public information and consumer education are important components of an overall strategy to address the environmental impacts of motor vehicles. Accessible information that rates car and light truck environmental performance can enable consumers to account for the environment in their purchase decisions, can 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 the *Green Guide to Cars and Trucks*, an annual, consumer-oriented booklet providing model-specific environmental information for the U.S. automotive market. In the United States, the only known antecedent is *The Green Buyer's Car Book* (Dyson et al. 1994), which was quite comprehensive regarding impacts covered, but technical in style and was published only once. A number of other green, consumer-oriented car books emphasize driving and maintenance behavior rather than vehicle choice, although some discuss fuel economy ratings (e.g., Sikorsky 1991; Makower 1992).

In Europe, Verkehrsclub Deutschland (VCD, "German Traffic Club") and companion organizations in other countries have published environmental ratings for a number of years. (e.g., VCD 1997). VCD cosponsored a seminar on vehicle rating and the resulting report is probably the most comprehensive discussion of car rating issues to date (T&E/VCD 1996). VCD's rating system was updated in 1997 to provide greater emphasis to CO_2 emissions; their approach also covers other use-phase impacts (including noise), manufacturing impacts, and recycled content, using a system that adds or subtracts points based on various vehicle attributes. The club has proposed a Europe-wide effort to develop uniform reporting requirements according to the principles of life-cycle assessment.

This report covers the data issues, key assumptions, and analysis methods used to develop the ratings used in ACEEE's *Green Guide to Cars and Trucks: Model Year 1999*. It summarizes the application of the methodology to the 1999 model year, highlighting results for major classes and technology types, and identifies research needs for updating and refining the methodology.

RATING DESIGN CONSIDERATIONS

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

Life-cycle assessment (LCA) techniques provide a framework for systematically considering environmental impacts and have been used for eco-labeling of other products (EPA 1993b, 1993c). Table 1 illustrates the range of environmental concerns to be considered over the phases of a vehicle's lifecycle in the form of a product assessment matrix. Letter codes in the matrix cells show items covered in the methodology described here. Only the use phase is well covered because of the data limitations encountered when attempting to develop vehicle model-specific assessments.

Use-phase energy and air pollution related effects do represent a substantial part of an automobile's life-cycle impacts. Roughly 90% of an average vehicle's life-cycle energy use occurs during its operation (Keoleian et al. 1997, Table 7.1). DeLuchi (1991) estimates that the full fuel-cycle GHG emissions of a gasoline powered automobile are 68% from fuel end use, 21% from fuel production and distribution, and 11% from vehicle materials and manufacturing processes. Thus, vehicle use accounts for 68% + 21% = 89%, closely matching the life-cycle energy use share as expected. Use-phase shares vary for other pollutants, being clearly high for carbon monoxide (CO) but lower for sulfur dioxide (SO_2). Moreover, use-phase energy and air pollution impacts are the focus of the vehicle-oriented public policies which our rating system is intended to complement.

At present, only three types of relevant, independently verifiable data cover all makes and models: (1) vehicle emissions data, addressing most aspects of use-phase air pollution; (2) vehicle fuel consumption data, addressing other aspects of use-phase air pollution as well as energy use and greenhouse gas emissions; and (3) vehicle mass data, addressing materials production and manufacturing impacts. A rating system must integrate these data along with parameters for weighting the various items in order to provide a model-specific index of life-cycle environmental impact.

Vehicle Emissions

Automotive emissions of criteria air pollutants 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, vehicles are required to meet emissions standards which regulate carbon monoxide (CO), hydrocarbons (HC), and nitrogen oxides (NOx), and particulate matter (PM). (To date, PM standards are enforced only for diesel vehicles, since gasoline vehicles have been considered to have negligible PM emissions.) Standardized emissions tests involve placing a vehicle on a chassis dynamometer and operating it over a simulated driving cycle while collecting samples of the exhaust. Tests are also made to detect fuel vapor leaks (evaporative emissions). Testing is the responsibility of automakers, who report the results to the U.S. Environmental Protection Agency (EPA) or the California Air Resources Board (CARB).

Standard emissions tests tend to significantly underpredict in-use emissions. Past data have revealed that lifetime average in-use emissions are 2 to 4 times higher than the nominal emission standards levels in grams per mile (g/mi) to which the vehicles are certified (Calvert et al. 1993; Ross et al. 1995). The reliability of its emissions control system (ECS), including engine operation which affects ECS performance, is a key determinant of a vehicle's lifetime real-world emissions.

EPA's mobile source emissions models incorporate degradation factors and other parameters to predict average emissions rates over vehicle lifetimes. Ross et al. (1995, 1998) analyzed extensive in-use data to estimate actual emissions for typical late-model vehicles, and their results form the basis for the in-use estimates used here. The Ross et al. estimates are broadly consistent with lifetime average predictions by the MOBILE5 emissions model (EPA 1996b). Nevertheless, substantial uncertainties remain, which is why Table 1 shows a "B" status for use-phase air pollution.

Fuel Consumption

Vehicle fuel consumption and the fuel supply cycle produce emissions of both greenhouse gases and criteria pollutants. These impacts are essentially proportional to the quantity of fuel consumed. Estimates of fuel economy (miles per gallon, or MPG) are derived from the same simulated driving tests as used for meeting emissions standards. Vehicles are labeled for fuel economy (separately for typical city and highway driving) based on these results. Procedures also exist to rate vehicles powered by electricity or other alternative fuels, which are labeled for fuel consumption as well as emissions (FTC 1996).

A vehicle's rate of fuel consumption drives its fuel-cycle impacts, which vary depending on the fuel and its source. For example, grid-connected electric vehicles, which may have zero vehicle emissions, entail a variety of powerplant emissions and other impacts depending on how the electricity is generated. Emissions factors (e.g., in grams of pollutant per Btu of fuel consumed) for GHG and criteria emissions are fairly well known based on national statistics. Thus, given fuel economy data, estimating a vehicle's fuel cycle impacts is straightforward and reliable for accurately discriminating among different models.

Manufacturing Impacts

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

Given these data limitations, environmental impacts of the materials production and manufacturing phases of vehicle life are best estimated in proportion to vehicle mass. Vehicle mass also is probably a good surrogate for end-of-life impacts, although we did not attempt to incorporate environmental statistics from this final phase of the life cycle. Developing better methods for rating vehicles according to environment impacts from assembly, parts production, and materials use remains an area for future work.

Integrating Methodology

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

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

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

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

$$EDX = \Sigma\, d_{ij}e_{ij}$$

Here, i is an index over emission species (air pollutants, including greenhouse gases), j is an index over locations of emissions, d_{ij} is an environmental damage cost (e.g., dollars per kilogram, \$/kg), and e_{ij} is the quantity of emissions averaged over a vehicle's operational life (e.g., grams per mile, g/mi). 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.

CHARACTERIZATION OF IMPACTS

Given the data availability as noted above, the above relation can be calculated on the basis of vehicle emissions, fuel cycle emissions, and emissions factors based on vehicle mass (for embodied energy and environmental impacts).

Vehicle Emissions

Some vehicle emissions are regulated and others are not. We estimate both. Regulated emissions include carbon monoxide (CO), non-methane organic gases, hydrocarbons (HC), nitrogen oxides (NO_X) and particulate matter smaller than 10 microns (PM_{10}). These emissions depend largely on the emissions standard to which a vehicle is certified and its fuel. Hydrocarbon vapors, also termed volatile organic compounds (VOC), are regulated according to particular definitions, such as non-methane organic gases (NMOG) defined in terms of photochemical reactivity. We model evaporative HC emissions as a function of both fuel consumption and emissions certification level. We estimate unregulated pollutants as a function of fuel type and consumption rate, independently of the emissions standard. The pollutants that are not directly regulated for motor vehicles but are incorporated in our rating system are sulfur dioxide (SO_2), methane (CH_4), nitrous oxide (N_2O), and carbon dioxide (CO_2).

Regulated In-Use Emissions from Vehicles up to 8,500 lb GVW

Tailpipe and evaporative emissions are regulated for cars and light trucks under both Federal and California vehicle emissions programs. We treat regulated tailpipe emissions as depending only on the emissions standard level to which a vehicle is certified, rather than on the particular test values submitted for certification. Emissions certification is designed as a pass/fail test, and manufacturers do not have legal requirements to maintain the test values they submit, only the standard levels to which they certify. Substantial variability can exist among test results for the same model vehicle and the number of tests on each model is very low. Therefore, we do not use certification test values as a basis for our estimates. Rather, we derive estimates based on published analyses of in-use emissions data, which are not model-specific. Emissions standard levels for each pollutant (CO, HC, NO_X, and PM_{10}) are adjusted to reflect expected in-use performance over a vehicle lifetime (not just the specified mileage durability requirements over the simulated test cycles which are required for certification). The detailed assumptions for estimated in-use emissions for each emissions standard are presented in a multi-part table (Table A1) in the appendix.

The in-use data which have been analyzed are for vehicles meeting standards ("Tier 0") less stringent than those in effect in MY1999. We extrapolate new vehicle in-use performance by separating the causes of emissions addressed by the tighter standards from those not addressed by the tighter standards. Our base estimates are for CO, HC, and NO_X for Federally certified (Tier 1) gasoline vehicles, following the approach of Ross et al. (1995, 1998) as adapted by Hwang (1997) for model year 1996 vehicles. This approach parses vehicle emissions into four sources: on-cycle, off-cycle, degradation, and malfunction, which sum to the total in-use emission rate.

To develop emissions factors for all classes and all standards, estimates for the Tier 1 LDV/LDT1 standards are scaled in two ways:

- for more stringent (California) standards (TLEV, LEV, ULEV), estimates for the component sources are scaled down;
- for heavier vehicle classes (LDTs, MDTs), estimates are scaled up.

Not all component sources (on-cycle, off-cycle, malfunction, and degradation) are treated the same way. For the California standards, we reduce the on-cycle and degradation sources in proportion to the standard values, but the off-cycle and malfunction sources remain fixed.

Ross et al. did not provide estimates for the light duty truck classes (LDT1–4). For these heavier vehicle classes, physical considerations imply emissions behaving in proportion to vehicle load (that is, mass). The standards are higher for heavier vehicles, and so for the sources (on-cycle and degradation) explicitly addressed by current standards and test procedure, we scale emissions in proportion to the standards level. We scale off-cycle and malfunction emissions by relative vehicle load, represented by the average inertial test weight (ITW) within each class. For example, all LDT2s have the same off-cycle emissions factor, which is derived using the ratio of average LDT2 ITW to average LDV ITW. This approach is applied to both gasoline and diesel vehicles and is detailed along with the resulting emission factors in Table A1.

For example, Table A1a documents our estimated emission rates for Federally certified (Tier 1) vehicles. For LDT2s, our on-cycle NO_x emission estimate is 0.46 g/mi, 1.75 times higher than the LDV rate, based on the ratio of the LDT2 to LDV standard (0.7 g/mi : 0.4 g/mi). The off-cycle emissions rate of 0.31 g/mi is 1.29 times as high as the LDV off-cycle rate, based on the ratio of average LDT2 ITW to average LDV ITW (4,500 lb : 3,500 lb).

For new California-certified vehicles, in-use data analyses have not yet been published either. We assume that off-cycle and malfunction emissions of vehicles certified to TLEV, LEV, and ULEV standards are the same as for Tier 1 vehicles, since the tighter standards do not explicitly address these sources of emissions. We assume that on-cycle and degradation emissions are reduced by the ratio of the California standard to the Tier 1 standard. As we did for Tier 1 LDTs, we scale off-cycle and malfunction emissions by load-based factors. The resulting in-use estimates are illustrated in Figure 1 for the principal standards in effect in 1999; calculation details for particular California standards are given in Tables A1b–d.

In spite of the now-established concern about the adverse health effects of fine particulate matter (PM) emissions, few data are available to characterize the impacts of motor vehicle PM at the make and model level. Most data, as used for example to develop PM emission inventories, are highly aggregate. Established inventory models, such as EPA's PART model, generally characterize PM_{10} (particulates up to 10 microns in diameter), while the greatest health concern is for much finer particles, typically in the sub-micron range. Characterization of PM, particularly ultrafine PM through particle count rather than mass-based measurements techniques, is an active area of research. At this point, PM emissions characterizations for motor vehicles remain highly uncertain. Delucchi (1997b) estimates Tier 1 gasoline LDV PM_{10} emissions of 0.042 g/mi. But recent data on vehicles with 3-way catalysts reveals significantly lower emission rates (Mark and Morey 1999, Durbin et al. 1997). Data including lifetime average real-world data on PM emissions are not available, so we assumed an emissions rate for LDVs that is half of our MY1998 PM_{10} rate, resulting in a MY1999 rate of 0.21 g/mi. PM_{10} emissions rates for LDTs and for California certified vehicles are scaled from the Tier 1 LDV rate as shown in Tables A1b-d.

Real-world data on diesel tailpipe emissions are even more limited than for gasoline vehicles. The Supplemental Federal Test Procedure (SFTP) final rule (Federal Register 1996) contains data on diesel NO_x emissions from a few manufacturers' test results for passenger cars only. The SFTP regulates off-cycle emissions by requiring the testing of vehicles over the US06 driving cycle, which includes more episodes of high power driving than the standard FTP cycle. To divide these emissions into on-cycle and off-cycle components, we adopt the SFTP estimates of 28% off-cycle and 72% on-cycle. Degradation and malfunction emissions for diesels are known to be very small, therefore we do not apportion the total tailpipe emissions into these two categories.

The SFTP final rule gives total (on-cycle plus off-cycle) tailpipe emissions estimates of 1.48 g/mi at 50,000 miles and 2.07 g/mi at 100,000 miles for NO_x plus HC, of which 88% is NO_x. We therefore take 88% of the average of the 50,000 and 100,000 mile estimates to get 1.56

g/mi NO_x and use the same SFTP apportionment of 28% off-cycle and 72% on-cycle. The scaling approach is similar to that for gasoline vehicles described above. On-cycle emissions are scaled by the ratio of LDT to LDV standards, while off-cycle emissions are adjusted by load-based scaling factors, as described in the Preface to Table A1. For CO and HC, we adopt the diesel LDV emission factors given in Mobile 5a model as given in document AP-42 Table 5.1.1 and shown in Table A1e of this report.

We also developed a set of emission factors for compressed natural gas vehicles (CNG) that meet California's ULEV and SULEV standards. Estimates of real-world tailpipe emissions for the vehicles are drawn from the GREET model (Wang 1996) and from Delucchi (1997b), as detailed in Tables A1f–g.

Methodology for Heavier Light Trucks

Vehicles between 8,500 lb GVW and 10,000 lb GVW (Class 2b trucks) are not subject to the same emissions and fuel economy regulations or data reporting and labeling regulations as LDVs and LDTs. An increasing number of these vehicles, however, are variants of LDTs and are sold as personal vehicles. We refer to these vehicles, having a GVW greater than 8,500 lb and up to 10,000 lb, as "Heavier Light Trucks" (HLTs). To include them in our ratings required the development of a procedure for estimating their lifetime average real-world emissions in a manner consistent with vehicles subject to light-duty regulations.

Since HLTs are exempt from CAFE standards, EPA does not collect fuel economy data. We mailed letters to manufacturers of HLTs requesting fuel economy data and related specifications for their HLTs. No automakers provided us with such data. Therefore, we developed a procedure for estimating HLT fuel economy and emissions by scaling from an LDT model of which the HLT is a variant. For example, the MY1999 2WD GMC Suburban is classified as an LDT4 and fuel economy and emissions certification information data for it are available in an EPA database. The 4WD variant (with some engines) is over 8,500 lb GVW, and so is not listed in the EPA database. Therefore, we estimate the MY1999 4WD (HLT) GMC Suburban fuel economy and emissions by scaling the estimates for a 2WD (LDT4) version having the same engine.

Vehicle Mass Estimation. The basis for our procedure is an estimate of vehicle mass, applied in the form of inertial test weight (ITW). We assume that ITW (as opposed to GVW) was only slightly higher for the HLT than for LDT version of a model, due to the mass of 4WD components or a more robust suspension, for example, that permits a higher GVW. Based on a review of manufacturer reported specifications from previous model years, we determine that a typical mass difference between a LDT and its corresponding HLT is 300 lb. So for each HLT evaluated, we add 300 lb to the EPA reported ITW for the matching LDT version to arrive at an estimated ITW for the HLT version.

Fuel Economy Estimation. To estimate HLT fuel economy, we scale from the corresponding vehicle's LDT fuel economy as described below. This scaling was done using mass sensitivity coefficients derived from the An and Ross (1993) fuel economy model. We used a coefficient of -0.27 for city fuel economy and -0.23 for highway. Given the small assumed mass differences, a linear approximation was used; in the city cycle case, for example:

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

where "m" designates mass (ITW) and MPG fuel economy and subscripts refer to ($_1$) the base LDT for which fuel economy is known and ($_2$) the HLT variant for which fuel economy needs to be estimated. These coefficients assume that other key vehicle parameters are constant; in particular, engine displacement is constant because we address only HLTs matched by engine and transmission type to a given LDT. Parameters which would also affect fuel economy, but for which we did not adjust, include gear ratios and the n/v (rpm per mph) ratio, and driveline friction, among others. For example, higher n/v and higher driveline friction in an HLT variant would push its actual fuel economy lower than what we estimate; however, these data were not readily available. Ideally we would like to have HLT fuel economy data from the standard LDV/LDT test cycles.

Emissions Estimation. To estimate tailpipe emissions, we assumed that HLT emission characteristics are not much higher than those of corresponding LDT versions. This assumption is based on discussions with EPA staff and other experts, which confirmed that emissions control technology is similar for both HLT and LDT versions of most light trucks, including, most notably, the use of 3-way catalysts for gasoline vehicles. We adopt, therefore, a method of scaling up emissions factors from LDT4 emission factors. We use a load-based scaling in which we multiply LDT4 emission factors by the ratio of average HLT ITW to average LDT4 ITW. These load-scaling factors are shown in Table A1 Preface and the resulting emissions factors in Table A1a for gasoline vehicles and Table A1e for diesels. Before settling on an approach, we investigated approaches similar to our method for LDTs of scaling up from LDV emission rates based on the ratio of HLT to LDV standards. HLT standards are so lax, however, that this approach produced unreasonably high results, given that the vehicles carry similar ECS technology.

To estimate evaporative emissions for HLTs, we scaled the LDV rates (see below) by the ratio of HLT to LDV evaporative standards (3.0 g/test : 2.0 g/test). This method is similar to the one used by EPA in the Mobile 5a model and is based on the fact that evaporative emissions test procedures are the same and that control equipment is largely the same for both HLTs and LDTs. See Table A2a for details.

Evaporative Emissions from Vehicles

Hydrocarbon vapors leak from fuel tanks, lines, and other fuel system components of a vehicle. These evaporative emissions are regulated by EPA and CARB by means of a test wherein stationary vehicles are placed in controlled chambers and subjected to a range of temperatures for a set amount of time. The mass of fuel evaporated is measured, giving results in grams of HC per test. For consistency with other aspects of our methodology, rather than grams-per-test levels we use evaporative emissions factors in grams-per-gallon, derived from Delucchi (1997b). Federal and California-certified vehicles meet the same gram/test standard. However, the California test procedure is more stringent, so we adjust the estimates downward for California-certified vehicles based on EPA (1997b). Following Delucchi (1997b), we assume negligible evaporative emissions for diesel and CNG vehicles. Details of our estimates for evaporative emissions are provided in Table A2a.

Unregulated In-Use Vehicle Emissions

Tailpipe emissions of SO_2, N_2O, CH_4, and CO_2 are not regulated by vehicle, although SO_2 emissions are linked to restrictions on fuel sulfur content. These emissions do not depend on a vehicle's certification level but are related to the amount of fuel consumed depending on fuel type. Delucchi (1997b) estimates these emissions on a g/mi basis, which we convert to a g/gal value using his assumed average fuel economy (MPG). Since Delucchi does not estimate light duty diesel emissions, but the fuel is the same for all vehicles, we use the heavy-duty diesel vehicle g/mi estimates and convert them to g/gal values. Of these emissions, SO_2 makes a significant contribution to health damages; N_2O, CH_4, and CO_2 are greenhouse gases. Estimation details are given in Table A2a.

Fuel-Cycle Emissions

Pollution occurs throughout the fuel production cycle, from the well head to the fuel pump for gasoline or from the coal mine to the wall plug for electricity, for example. HC emissions associated with refueling are included as part of these fuel cycle emissions, but those that occur once fuel is in a vehicle are included under *Evaporative Emissions,* above. Delucchi (1997b) models full fuel-cycle emissions of CO, HC, NO_X, PM_{10}, SO_2, CH_4, N_2O and CO_2 for gasoline, diesel, CNG, electricity, and other alternative fuels. His results are expressed in g/MBtu (grams per 10^6 Btu) and those relevant to our analysis are detailed in Table A2b. We then computed grams-per-miles estimates from each vehicle's estimated in-use fuel economy, which is estimated as described below.

Fuel Economy and Shortfall

Though not perfect, the certainty level for fuel economy is much better than that for vehicle emissions. Simulated driving tests overestimate fuel economy—MPG is higher on the test cycles than in real-world driving—but the bias is fairly well known. Since 1984, EPA has adjusted city MPG downward by 10% and highway MPG downward by 22% for labeling purposes. These adjustments imply a "shortfall" of roughly 15% compared to the composite 55% city, 45% highway MPG used for Corporate Average Fuel Economy (CAFE) compliance purposes. Changing traffic conditions appear to have increased fuel economy shortfall of on-road vs. test fuel economy and the available evidence suggests that it varies with vehicle class, being worse for many light trucks (Mintz et al. 1993). Therefore we adjusted the composite (CAFE-compliance, rather than label) fuel economy downward by 18.7% for cars and by 20% for light trucks. The error remaining after such adjustments is probably less than 10%. This modest uncertainty in fuel consumption rates is a marked contrast to the situation for vehicle emissions rates, where residual errors are quite large and only crudely quantifiable (e.g., within a factor of 2 or more).

All emissions associated with charging an electric vehicle (EV) fall under the fuel-cycle category. We used power consumption (kWh/mi) data supplied directly by automakers for their electric vehicles; we list these data as an efficiency rating (mi/kWh) in our tables. Electricity losses during recharging are included in the EV efficiency rating, so the fuel-cycle emissions factors reflect electricity generation and distribution losses, but not the losses associated with end-use charging equipment. We use DOE (1997) estimates for a national average power generation mix as detailed in Table A2c. Our valuation assumptions for health effects treat power plant emissions differently than vehicle emissions; as discussed below, this issue (related to differences in exposed population) is more important than the geographic differences in electricity generation mix.

To facilitate comparisons among fuels, direct CO_2 emissions and full fuel-cycle CO_2-equivalent GHG emissions are summarized by fuel in Table A4. For gasoline, for example, full cycle accounting results in greenhouse impacts roughly 60% higher than the CO_2 directly released during combustion.

Manufacturing Emissions

Energy is consumed in the assembly of vehicles and to an even greater extent is embodied in the production of raw materials. We characterize the associated impacts by averaging aggregate automobile manufacturing sector statistics over an assumed 100,000 mile vehicle lifetime.

For GHGs, we start with the DeLuchi (1991) estimate of CO_2-equivalent emissions associated with vehicle manufacturing as 55.9 g/mi for a 2187 pound car, implying an mass-based emissions factor of 0.056 g/mi per kg of vehicle.

For NO_X, SO_2, and PM_{10}, we estimate the emissions associated with energy use for materials production and manufacturing, also assuming proportionality to mass. This procedure involves three principal inputs:

1. Mass fractions of major materials (metals, plastics, rubber, glass, etc.) in an average vehicle;

2. Energy use by fuel (electricity, coal, oil, natural gas) for producing each material (e.g., joules per kilogram of material);

3. Manufacturing and electric power generation emissions factors by pollutant for each fuel (e.g., grams of NO_X, SO_2, and PM_{10} per joule of fuel consumption).

These calculations are detailed in Table A3. The resulting emission factors in g/mi per kg of vehicle mass are shown here in Table 2.

To address environmental impacts not associated with manufacturing phase energy consumption, we include releases of toxic pollutants as accounted in Toxic Releases Inventory (TRI) data. Based on data for US auto plants, Keoleian et al. (1997), give a summary estimate of 8.9 lb of TRI releases and 15.1 lb of TRI transfers per vehicle as of 1993. We assume that transfers are an order of magnitude less damaging than releases, giving a toxic release-equivalent of 8.9+1.5 = 10.4 lb, or 4.72 kg, per vehicle. Using the 1993 average light vehicle curb weight of 1460 kg implies 3.23 g/kg, i.e., 3.23 grams of toxic emissions per kg of vehicle, representing embodied TRI impacts.

IMPACT VALUATION AND RESULTS

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

In economic terms, most environmental impacts are considered externalities, that is, effects on others which are not accounted for in market transactions by the parties causing the effects. Delucchi (1997b) places the human health externalities of air pollution from U.S. motor vehicle use at $24 – $450 billion per year (1991$). These estimates correspond to a per vehicle external cost of $140 – $2500 per year. The large range reflects the uncertainty inherent in such estimates; nevertheless, the evidence is quite strong that the costs are non-zero.

Environmental Damage Costs

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

The harm caused by air pollution depends on where it is emitted relative to exposed populations and other subjects of concern. Transported pollutants are subject to dilution and transformation. The impact of, say, one gram of PM emitted from a vehicle tailpipe differs substantially from the impact of one gram of PM emitted from a power plant. Thus, a single damage cost value should not be used for a given pollutant independently of where it is emitted. Delucchi and McCubbin (1996) examined this issue in some depth for the major pollutants associated with motor vehicles and their supporting infrastructures (including manufacturing plants, petroleum refineries, electric utilities, etc.). They simulated the fraction of a pollutant, emitted from a given source, which would reach exposed subjects in various locations. Their simulation results were normalized relative to exposures to light duty vehicle PM emissions, yielding what might be called damage cost reduction factors. Reviewing the wide range of resulting factors, we selected a factor of 10 for reducing the damage cost of pollutants from electric utilities relative to those from vehicles. We selected a reduction factor of 5 for factories and refineries, which entail relatively higher worker and community exposures.

For base damage costs—those representing the impacts of pollutants directly emitted from motor vehicles—we adopted the geometric means of the low and high health cost estimates of Delucchi (1997a, Table 1-A1). The resulting estimates for major pollutants by location are shown in Table 3. These estimates place a relatively high value on reduction of fine PM and its precursors (particularly SO_2 and NO_X). In contrast, earlier estimates emphasized reduction of ozone and its precursors (resulting in a relatively high value for avoided HC emissions, e.g., as in the review by Wang and Santini 1995). Established vehicle regulations place a high premium on ozone reduction, with a strong emphasis on reducing HC. California's smog index (CARB 1996) matches the type of valuation implied, for example, by Wang and Santini (1995) estimates, in which the damage cost ($/kg) of HC is about 50% of that of NO_X. By contrast, the damage cost of HC is only 8% of that of NO_X for the Delucchi (1997a) estimates which we adopt here. Thus, our valuations imply relatively small differences among current California standards, which are strongly oriented to HC reduction and cut NO_X by only a factor of two from the Federal level. Our valuations would reflect a significantly greater benefit for California's proposed LEV-2 standards, which would cut nominal NO_X emissions by a factor of eight from the current Federal level (CARB 1997b). See Sensitivity to Key Parameter Choices below for further discussion.

Since the average U.S. electricity generation mix includes a significant share (19%) of nuclear power, it is necessary to include a measure of the environmental damage associated with the nuclear fuel cycle. Its environmental impacts fall largely outside of the criteria air pollutant and greenhouse gas impacts on which we base our damage cost estimates for fossil fuels and their products; nuclear power has very small criteria and GHG emissions compared to fossil sources. External costs of nuclear power have been extensively investigated for electric sector studies. Population exposures to radiation occur during uranium extraction and processing to produce nuclear fuel, during normal reactor functioning, and there are exposures associated with 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 (e.g., Chernobyl), but are rare and unpredictable and so are very poorly amenable to statistical characterization.

Ottinger et al. (1991, 34) provide summary external cost estimates of 0.11 ¢/kWh for routine operations, 0.50 ¢/kWh for decommissioning, and 2.3 ¢/kWh for accidents. The accident portion is based largely on allocating the damage estimates associated with the Chernobyl disaster over the operating history base of nuclear power. (Impacts of the worst U.S. accident, at Three Mile Island, are nearly negligible in comparison to Chernobyl.) Given the relatively safe history of U.S. nuclear operations, and the high uncertainty associated with accident estimates, we use only the two non-accident costs, implying an external cost of 0.61 ¢/kWh for nuclear power as part of the U.S. average electricity generation mix. As shown in Table A2c, prorating this estimate by the 18.6% share of nuclear power in the mix adds 0.11 ¢/kWh to the overall external cost of electricity, as used to calculate the environmental damage from electric vehicle use.

Damage cost estimates for toxics are not readily available. The TRI includes an extensive list of substances, many of which are hydrocarbons, but their control concerns are as much for toxicity as for ozone formation, and some are metallic compounds, including carcinogens, mutagens, etc. We treat these TRI-based emissions as if they were PM_{10} released at manufacturing sites. For our EDX calculations, we add the toxics estimate to the PM emissions embodied in manufacturing energy use. Multiplying the resulting PM emission factor (3.64

g/kg) by the damages cost factor for manufacturing PM emissions ($7.22/kg) implies a cost of $26.28/tonne of vehicle.

It is extremely difficult, if not impossible, to estimate meaningful damage costs for greenhouse gas (GHG) emissions. Published estimates tend to be relatively small in magnitude. For example, based on a literature review of GHG damage estimates, Delucchi places aggregate global warming externalities from U.S. motor vehicle use at over a factor of 30 lower than air pollution health externalities (Delucchi 1997a, Table 1-9A). A number of analysts have examined GHG control (mitigation) costs and the span is quite wide. For example, costs of carbon sequestration through reforestation range from $\$2/T_C$ for plantations in Central America to $\$200/T_C$ for plantations in North America (Ottinger 1990, 165-185; "T_C" refers to metric tons expressed on a carbon-mass basis). Global warming, like other issues of sustainability, transcends traditional analyses. Concern is well established in the scientific community (IPCC 1995). The Kyoto Protocol adopted in December 1997 commits developed nations to net reductions of their GHG emissions over the next 10–15 years.

In light of these considerations and our environmental point of view, we treat GHG emissions as equally important to traditionally regulated air pollutants in determining the rating of an average vehicle. To effect such a weighting, we calculated a quasi-damage cost for CO_2-equivalent GHG emissions so that, for an average 1999 vehicle, one-half of the EDX would be GHG-related and the other half would be equal to the sum of the health damage costs from other pollutants (the total estimated health effects of PM, NO_X, VOC, etc.). The resulting value is $\$63/T_C$, or $0.0171/kg on a CO_2-equivalent mass basis.

Summary of Life-Cycle Estimates

We compiled a data base of all new light duty vehicles on the U.S. market in 1999 and carried out the rating analysis for each make and model (1,464 in all). Figure 2 shows the resulting EDX distribution: (a) for the overall light duty fleet and (b) separately for cars and light trucks. These results are not sales-weighted and so represent the "menu" of vehicles offered to the market, as opposed to market outcome. The 1999 EDX results range from 0.85¢/mi (a small electric vehicle) to 4.7¢/mi (a large, 4-wheel drive sport utility vehicle). The median is 2.6¢/mi and one-half of the models fall between 2.3¢/mi and 3.2¢/mi. Here, an explanation of the calculations and results using base-case parameters is followed by a discussion of the sensitivity of the EDX to key parameter choices.

Table 4 details the EDX calculation for an average 1999 vehicle using base-case parameter values. The first three parts of the table itemize health-related criteria emissions impacts for: (a) direct vehicle emissions; (b) fuel-cycle emissions; and (c) emissions embodied in materials and vehicle assembly. Lifetime average (grams per mile) emissions rates are multiplied by damage costs from Table 3 to obtain life-cycle cost estimates in cents per mile (¢/mi). For criteria emissions, the three components are 0.79¢/mi (60%) at the vehicle, 0.29¢/mi (22%) from the fuel-cycle, and 0.25¢/mi (19%) embodied, summing to 1.32¢/mi (100% of life-cycle criteria emissions impact as calculated here).

Greenhouse gas (GHG) emissions calculations are shown in Table 4d. Emissions from each source, drawn from parts (a)–(c) of the table, are summed and then multiplied by the global warming potential (GWP) that represents the radiative forcing of each GHG species compared to that of CO_2 (Delucchi 1997b). The total lifetime average CO_2-equivalent emission rate (770 g/mi for the example shown) is then multiplied by the quasi-damage cost chosen for GHG emissions. The GHG impact and health-related (criteria emissions) impact are the same (1.32¢/mi) by definition, under our assumption that GHG emissions are to be as important as criteria emissions in determining the average vehicle's EDX. The GHG total breaks down as 68% at the vehicle, 19% from the fuel-cycle, and 12% embodied, similarly to criteria emissions. The calculations are summarized in Table 4e, showing the resulting total EDX of 2.64¢/mi.

Figure 2 illustrates how U.S. vehicles fall into two major classes: passenger cars (coupes, sedans, station wagons) and light trucks (pickups, minivans, and sport utilities). The distributions are bimodal because of the different regulatory treatment of cars and light trucks. The EDX for the median passenger car is 2.39¢/mi, while that for the median light duty truck (LDT) is 3.18¢/mi, about 33% higher.

Most light trucks fall into the LDT2 category. For an LDT2, for example, the U.S. federal NO_X standard is 0.7 g/mi, 75% higher than the car standard of 0.4 g/mi. The differences in emissions are compounded by differences in fuel economy standards, which were 27.5 MPG for cars and 20.7 MPG for light trucks in 1999 (implying a 33% higher fuel consumption rate for the trucks). The mass disparity between the car and light truck classes serves to further reinforce the bimodality. Since light trucks account for nearly 50% of sales, the environmental impacts of the 1999 vehicle cohort over its 12+ year lifetime will be dominated by light trucks.

Sensitivity to Key Parameter Choices

We examined the sensitivity of the EDX to several key parameters: the quasi-damage cost assumed for GHG emissions, the relative damage costs for different criteria air pollutants, and the location-dependent damage attenuation factors. Figure 3 presents sensitivity analysis results for nine representative vehicles. This figure shows results normalized to the average 1999 light duty vehicle. The base-case results are in Figure 3a, where the 1.0 relative EDX for the average 1999 light duty vehicle corresponds to the 2.64¢/mi bottom-line of Table 4.

Parts (b) and (c) of Figure 3 show the sensitivity to our assumption that GHGs are as important as criteria emissions. Halving the GHG quasi-damage cost (Figure 3b) lowers the relative EDX for EVs slightly, because power plant CO_2 emissions are de-emphasized. Diesels now rate worse, because their higher tailpipe emissions become more important. In this case, electrics appear to be a much better choice, with a relative EDX less than half that of diesels. The converse is true for doubling the GHG cost (Figure 3c); electrics then have an EDX only about 33% lower than diesels, and diesels appear better than LEVs.

Figure 3d examines criteria pollutant damage costs that emphasize ozone damages much more than damages from fine particulate matter (PM). Current vehicle regulations emphasize ozone control. However, recent revisions to the U.S. air quality standards significantly increase the emphasis on controlling fine PM. These revisions reflect current epidemiological findings.

This greater PM emphasis underlies our base-case damage cost assumptions. Ozone-emphasis damage assumptions lower the EDX of both electric and diesel vehicles relative to the base case. Diesels fare better because of the lower emphasis on PM damages and the diesel's very low HC emissions. Electrics fare better because of the de-emphasis of PM and its precursors (particularly SO_X), of which electric power plants are major sources, and their elimination of vehicular HC emissions.

Cases (e) and (f) examine the sensitivity to assumptions about dispersion and dilution effects for health-damaging air pollutants. Electric vehicle ratings are most sensitive to the relative importance of vehicular versus remote emissions. As shown in Figure 3e, doubling the attenuation factor—a not unreasonable assumption if one looks at the range of dispersion results in Delucchi and McCubbin (1996)—lowers an electric's EDX relative to its comparably sized counterparts. The effect of a zero damage attenuation assumption, as in Figure 3f, is more dramatic. The diesel vehicle then looks best overall, because it has such low fuel cycle emissions. The electric vehicle rates even worse than the larger, average LDV. However, such an assumption—e.g., that a gram of PM emitted from a power plant stack is just as damaging as a gram of PM emitted on an urban street—is not reasonable from a public health perspective, because the population exposures are so different.

Across all the cases in Figure 3, it is notable that the relative damages of light truck class vehicles are not very sensitive to changes in assumptions. The reason is that, compared to cars, light trucks emit more across the board—more tailpipe emissions of all species as well as more GHG and fuel cycle emissions. So changing the various valuation parameters has little impact on light trucks scoring more poorly than cars.

Public Presentation of Results

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

The Green Score allows comparisons both within and across classes. It is not tied to a particular model year and so it can accommodate updates to the methodology while maintaining a consistent scale for consumers. It also leaves room to reflect future improvements in vehicle environmental performance. To map the EDX from a [0,∞] range inversely to the Green Score on a [0,100] range, we use a gamma function to spread out the scores for future "green" vehicles at the expense of less differentiation among current vehicles. Presently, in fact, the variability in EDX within most vehicle classes is relatively small. The mapping, shown in Figure 4, is:

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

with a = 100, b = 3 and c = 5.76¢/mi. A perfect score of 100 is unattainable since it would require an EDX of 0. Using the parameters shown, model year 1999 Green Scores range from 7 to 57 and the average is 21.

Table 5 presents EDX and Green Score results for a variety of past, present, and hypothetical future vehicles. A "pre-control" vehicle, e.g., a typical early 1960s car with no emissions controls, weighing 4500 pounds and getting 14 MPG, would have an EDX of 6.9¢/mi and a score of 3. A roughly doubled-efficiency (53 MPG) 2290 pound gasoline that also met a "real-world" LEV standard would have an EDX of 1.4¢/mi and a score of 42. An ultra-clean gasoline vehicle meeting the PNGV (1994) tripled-efficiency goal would have a score of 58. Green Scores could become much higher if low-carbon fuels become available, potentially exceeding 90 for ultralight fuel-cell vehicles as envisioned by Lovins (1995).

When car shopping, most consumers target a given vehicle class and are unlikely, for example, to consider a subcompact when looking for a minivan. To facilitate comparisons within classes, we developed the symbolic, five-tier class ranking scheme shown in Table 6. In assigning class rankings, we considered the number of vehicles in each class and natural breaks in the distribution rather than rigidly applying the cutpoints listed in the table. An additional constraint was that no vehicles that scored worse than the model year average (an EDX of 2.78¢/mi, corresponding to a Green Score of 21) could obtain the Superior ranking. Details of the EDX distributions and exact cutpoints used for each class are provided in Appendix B.

AREAS FOR FUTURE WORK

This methodology provides a flexible framework that can be refined and updated as new data become available. The parameters and assumptions described in this document reflect updates made since the original 1998 edition. (Appendix C describes the updates made for this current edition.) Several areas for improvement are highlighted below and the authors look forward to receiving comments regarding other methodological issues to address.

In-Use Emissions

Characterization of in-use vehicle emissions is an ongoing area of effort. A multiyear time lag occurs from when a new vintage of vehicles is sold until in-use experience accumulates, data are gathered, and analysis is reported. Thus, it is necessary to rely on past data and modeling projections. Though not exactly following MOBILE-5b, the U.S. EPA's current vehicle emissions model, our estimates have been generally consistent with it. When the 1999 *Green Guide to Cars and Trucks* was released, EPA was in the process of finalizing MOBILE-6, and we expect to draw heavily on it as well as its supporting data and analyses for the next edition of our guide. Vehicles certified to the more stringent California standards and the Tier 1 federal standards phased into the fleet since 1994 appear to have substantially better in-use performance than had been observed historically. Additional improvements are expected in MY2000 with the phase-in of the Supplemental Federal Test Procedure (SFTP), which requires better control of off-cycle emissions. ACEEE will continue to review data and adjust the in-use emissions parameters for each new model year. A greater commitment by government and industry to perform and report extensive and realistic in-use emissions monitoring will be most valuable for improving both government emissions analysis and our rating methodology.

Materials Use and Manufacturing Impacts

As noted earlier, the materials production and manufacturing (as well as end-of-life) phases of the vehicle life cycle are poorly represented in the current methodology. The reason is lack of data linked to makes and models. Room exists for further consultation with LCA experts, discussions with the industry, with federal and state agencies involved in industrial pollution issues, and other experts. Nevertheless, data limitations will remain a constraint unless an industry-wide system for gathering and reporting the relevant data is developed. Given sufficient research resources and opportunities for collaboration with academic, industry, and environmental experts, we hope to explore these issues further. If interest exists, we are open to holding a workshop or series of meetings that can lead to the development of improved characterizations of pre- and post-use phase impacts, including ways to rate material production, supply chain, assembly, recyclability and recycled content, and end-of-life management.

Consumer Response Studies

The *Green Guide to Cars and Trucks* is still a relatively new concept, the first edition having been released on March 17, 1998. The understandability and usefulness of green rating information and how it is presented need to be investigated. It will be useful to solicit views and recommendations from market researchers and behavioral scientists who have experience in environmental ("green") purchasing generally, the automotive market, or both, as well as to perform market research on the *Guide* itself. ACEEE will pursue such studies and will also coordinate with others in government, industry, and other organizations who are also interested in exploring consumer acceptance of new vehicle technologies and related topics regarding the potential for "green" buying in the automotive sector.

CONCLUSION

Developing and refining the *Green Guide to Cars and Trucks* involves exploring many issues related to the life-cycle environmental impacts of vehicles and how they might be communicated to consumers. The resulting ratings provide new opportunities to foster a market for advanced technologies that can greatly reduce motor vehicle environmental burdens as well as for greener vehicles generally. Application, evaluation, and further development of environmental ratings for vehicles holds promise for aiding progress toward an environmentally sustainable automotive industry. ACEEE welcomes suggestions for improving the *Green Guide to Cars and Trucks* in terms of both rating methodology and presentation.

Table 1. Life Cycle Assessment Matrix for Application to Motor Vehicle Green Ratings

Environmental Concern	Phase of Product Life Cycle				
	Materials Production	Product Manufacture	Product Distribution	Product Use	End of Life
Air Pollution	C	C		B	
Energy Consumption	C	C		A	
Greenhouse Gas Emissions	C	C		A	
Land Contamination					
Noise					
Water Pollution					
Worker/Community Health					
Other Ecosystem Damage					
Other Resource Consumption					

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

Table 2. Evaluation of Impacts from Vehicle Manufacturing (Embodied Emissions)

Pollutant	grams of pollutant per kg of vehicle (a)	Damage Cost \$/kg pollutant (b)	Cost \$/tonne of vehicle
NO_X	19.8	0.90	18
SO_2	24.3	4.25	73
PM_{10}	3.64	7.22	26
Subtotal			117
CO_2 (c)	5600	0.0175	98
TOTAL			**215**
Cents per pound of vehicle			9.8
Cents per pound of vehicle per mile (assuming 100,000 mile lifetime)			9.8×10^{-5}

(a) Derived as described in text, with details given in Appendix Table A3.
(b) See discussion and Table 3, below.
(c) Derived from DeLuchi (1991), Table 9, estimate of 55.9 g/mi for a 2187 lb car.

Table 3. Damage Cost Estimates for Principal Air Pollutants

POLLUTANT	MARGINAL COST BY LOCATION OF EMISSIONS 1991$/kg		
	Motor Vehicles[a]	Refineries and Factories[b]	Electric Power Plants[c]
Carbon Monoxide (CO)	0.03	0.006	0.003
Hydrocarbons (HC, or VOC)	0.34	0.068	0.034
Nitrogen Oxides (NO_X)	4.50	0.90	0.45
Sulfur Dioxide (SO_2)	21.26	4.25	2.13
Particulate Matter (PM_{10})	36.12	7.22	3.61

(a) Geometric mean of low and high health cost estimates from Delucchi (1997a), 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.

Table 4. Environmental Damage Index (EDX) Calculation for an Average 1999 Vehicle

Vehicle attributes

Emissions	Tier 1 (prevailing Federal standard)
Fuel Economy	24.6 MPG (composite EPA test), 20.0 MPG (on-road)
Mass	3690 lb (1674 kg)

(A) Emissions at the Vehicle

Regulated Emissions by species	Emissions Standard grams/mile	Implied Adjustment Factor†	Real-world emissions grams/mile	Damage Cost $/kg	Life Cycle Cost cents/mile
CO	3.40	2.8	9.5	0.03	0.028
HC	0.25	2.4	0.60	0.34	0.020
NO_X	0.40	2.6	1.04	4.50	0.468
PM_{10}	0.08	0.3	0.02	36.12	0.075

Fuel-Dependent Emissions by species	Emissions Factor grams/gallon	Emissions Rate grams/mile	Damage Cost $/kg	Life Cycle Cost cents/mile
Evaporative HC	13.9	0.70	0.34	0.024
SO_X	1.62	0.08	21.26	0.172
CH_4	4.43	0.22	--*	
N_2O	3.25	0.16	--*	
CO_2	8200	410	--*	

Subtotal (a): health-related pollution impacts at the vehicle (cents/mile) 0.79

(B) Emissions from the Fuel Supply Cycle

Fuel-Dependent by species	Emiss. factor grams/gallon	Emiss. rate grams/mile	Damage cost $/kg	Life cycle cost cents/mile
CO	6.25	0.31	0.006	0.0002
HC	6.13	0.30	0.068	0.002
NO_X	8.50	0.43	0.90	0.038
PM_{10}	0.96	0.05	7.22	0.035
SO_X	9.88	0.49	4.25	0.208
CH_4	16.6	0.83	--*	
N_2O	0.18	0.01	--*	
CO_2	2450	122.5	--*	

Subtotal (b): health-related pollution impacts from fuel supply (cents/mile) 0.29

†Ratio of estimated real-world emissions to emissions standard, resulting from the procedure described under "Estimating In-Use Tailpipe Emissions" in the text.

*Greenhouse gas with negligible health damage; these emissions are incorporated below, in part (e).

Table 4. EDX Calculation for an Average 1998 Vehicle (continued)

(C) Emissions Embodied in the Vehicle

Species	Emissions factor grams/mile per tonne	Emissions rate grams/mile	Damage cost $/kg	Life cycle cost cents/mile
NO_X	0.198	0.33	0.90	0.030
PM_{10}	0.004	0.06	7.22	0.044
SO_X	0.243	0.41	4.25	0.173
CO_2	56.0	93.7	--*	
Subtotal (c): health-related pollution impacts from production phase (cents/mile)				**0.25**

(D) Greenhouse Gas Emissions from all Sources

source: species	At Vehicle grams/mile	Fuel Cycle grams/mile	Embodied grams/mile	Global Warming Potential (GWP)	CO_2-equiv. Grams/mile
CO_2	410.0	122.5	93.7	1	626.2
HC	1.30	0.31		2	3.2
NO_X	1.04	0.43	0.33	4	7.2
CO	9.5	0.31		5	49.0
CH_4	0.22	0.83		22	23.2
N_2O	0.16	0.01		355	60.9
Sum weighted by GWP	525.9	148.2	95.0		
Total CO_2-equivalent GHG emissions, grams per mile					769.7

Assumed damage cost factor for GHG emissions, per kg CO_2-equivalent	$0.0171
Subtotal (d): GHG impacts (cents/mile)	**1.32**

(E) Summary of EDX Calculation for an Average 1999 Light Duty Vehicle

Environmental Impact	Life Cycle Cost cents/mile
(a) At the vehicle health-related pollution	0.79
(b) Fuel cycle health-related pollution	0.29
(c) Embodied health-related pollution	0.25
Subtotal, health-related pollution (criteria emissions) impacts	1.32
(d) Subtotal, greenhouse gas impacts	1.32
TOTAL Environmental Damage Index (EDX)	**2.64**

Table 5. Green Scores for Selected Model Year 1999 Vehicles plus Past and Future Vehicles

Vehicle	Weight lbs [a]	Efficiency MPG [b]	Emissions Standard	EDX ¢/mi	Green Score
Fuel cell vehicle, renewable hydrogen [c]	1845	80	ZEV	0.18	88
3x passenger car, ultra-clean PNGV [d]	2290	80	ULEV-2	0.82	58
Best 1999 vehicle: GM EV1 [e]	3250	49	ZEV	0.85	57
2x passenger car, clean LEV [f]	2290	53	LEV	1.37	42
Average 1999 car	3285	28	Tier 1	2.64	20
Average 1989 car	3047	28	Tier 0	3.10	16
Average 1999 light truck	4286	21	Tier 1	3.26	15
Worst 1999 vehicle: Large SUV	5500	14	Tier 1	4.71	7
Pre-control car (1960s vintage) [g]	4500	14	none	6.85	3

(a) Test weight (curb weight plus 300 lbs).

(b) Composite unadjusted city/highway average gasoline equivalent MPG, based on 125,000 Btu/gallon.

(c) Assumes zero vehicle and fuel cycle emissions for hydrogen produced by solar-powered electrolysis, that curb weight is cut by half, and a 1%/yr decline in manufacturing emissions through 2010 (the assumed year of vehicle manufacture).

(d) Assumes improvements in real-world emissions control so that all vehicle sources (on-cycle, off-cycle, degradation, and malfunction emissions) are reduced by the ratio of California's proposed ULEV-2 standard to the Tier 1 standard; (ULEV-2 reduces NO_x to 0.05 g/mi); refer to Table A1d.

(e) The MPG-equivalent is derived from the EV1's rated consumption rate of 0.28 kWh/mi (3.6 mi/kWh), accounting for the different energy efficiencies of electricity supply (31%) and gasoline supply (83%). On an end-use only basis (3412 Btu/kWh), the efficiency would be 131 MPG-equivalent.

(f) Vehicle efficiency and mass are based on Duleep (1997) and we further assume improvements in real-world emissions control so that all vehicle emissions sources are reduced by the ratio of the LEV standard to the Tier 1 standard; refer to Table A1c.

(g) Assumes vehicle emissions of 84 g/mi CO, 20 g/mi HC, and 4 g/mi NO_x (Hwang 1997, 2).

Table 6. Percentile Guidelines and Symbols for Within-Class Vehicle Rankings

Percentile Guidelines	Class Ranking	Symbol
95% +	Superior*	✔
80% – 95%	Above Average	▲
35% – 80%	Average	○
15% – 35%	Below Average	▽
0 – 15%	Inferior	✖

*For a Superior ranking, a vehicle must also have a Green Score no less than the overall average, which is 21 (corresponding to an EDX of 2.78 ¢/mi) for MY1999.

Figure 1. Lifetime Average In-Use Tailpipe Emissions for Gasoline Cars

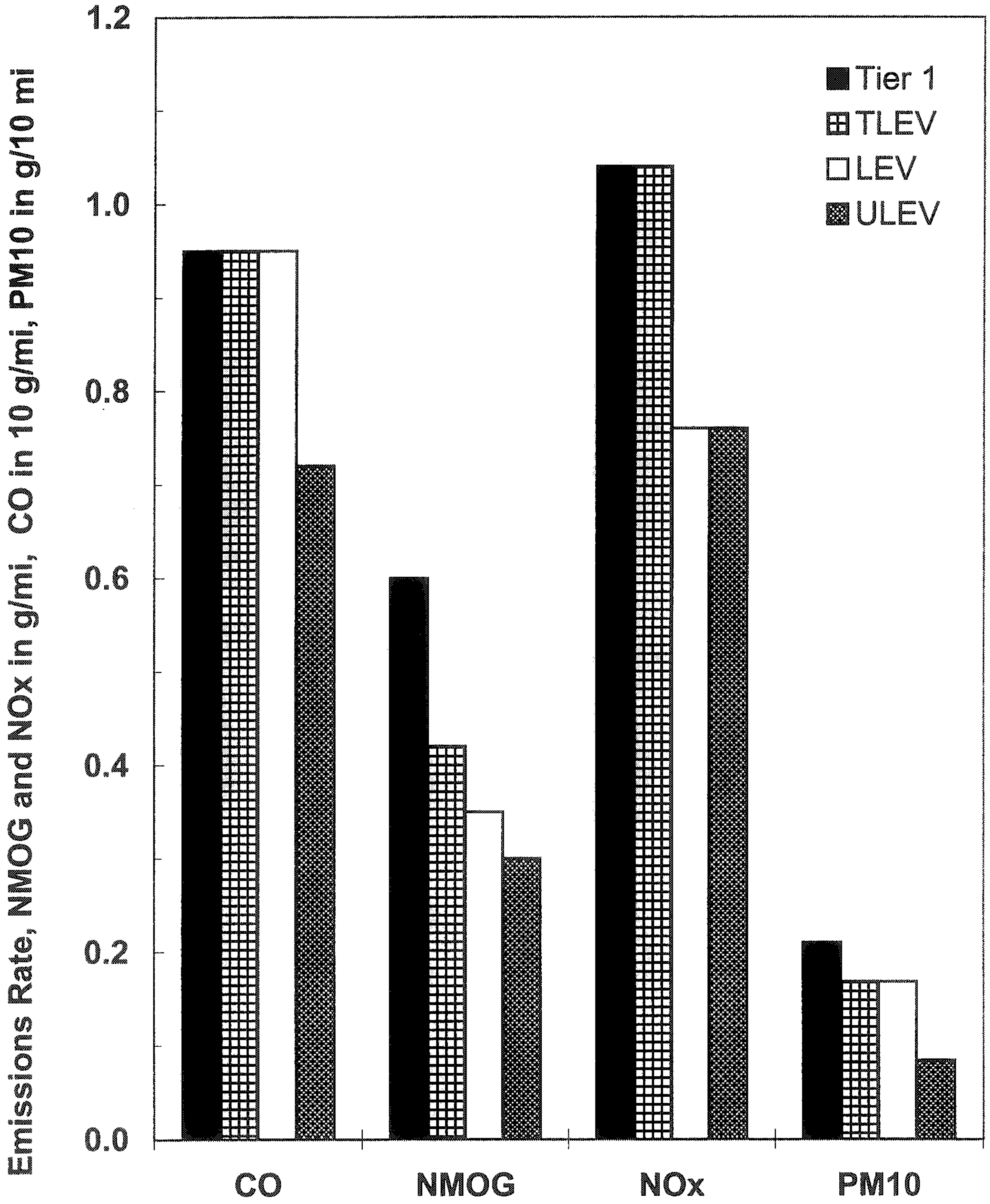

Figure 2. Distribution of Environmental Damage Index for Model Year 1999

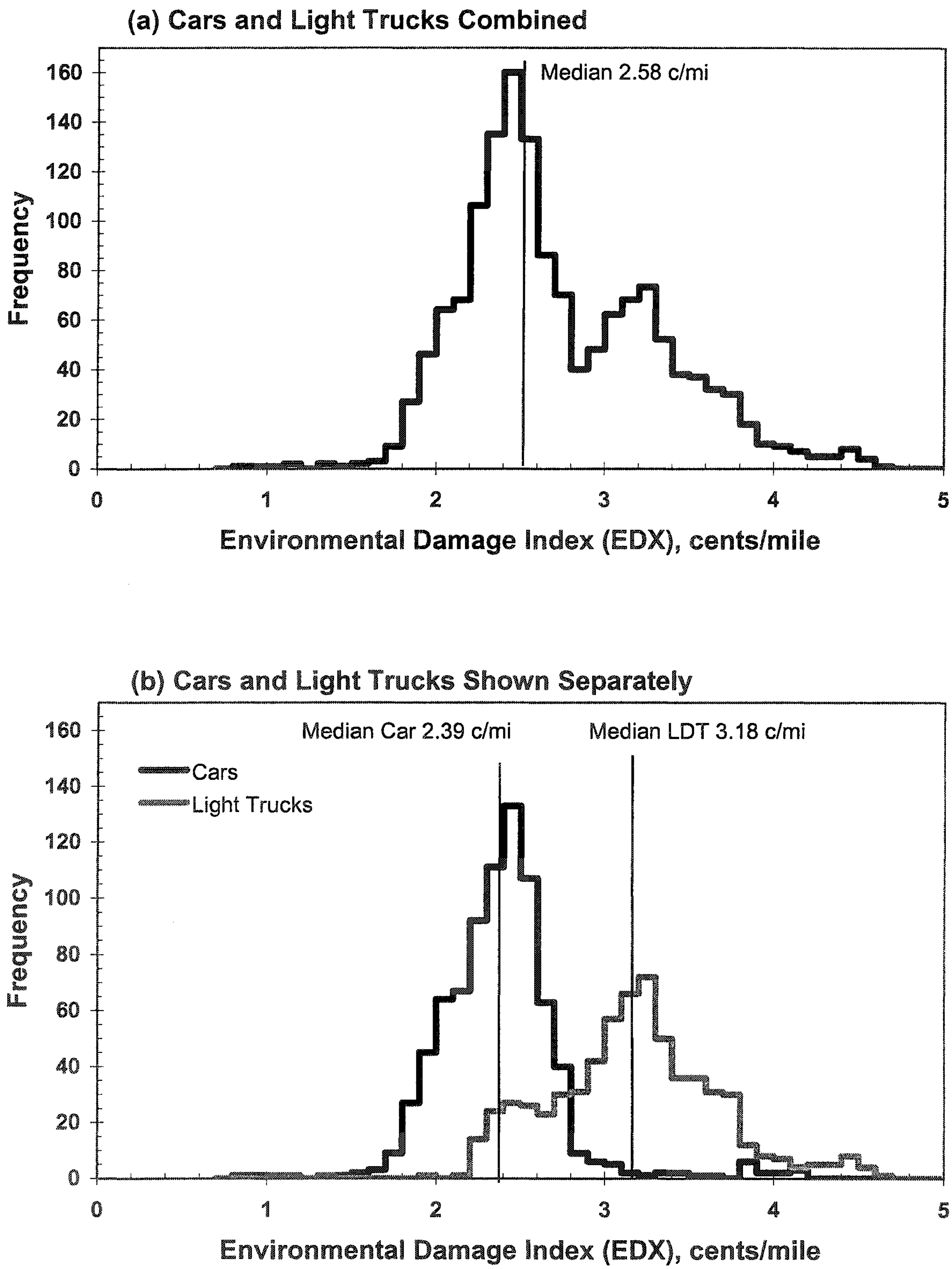

Figure 3. Sensitivity of Environmental Damage Index to Variations in Key Parameters

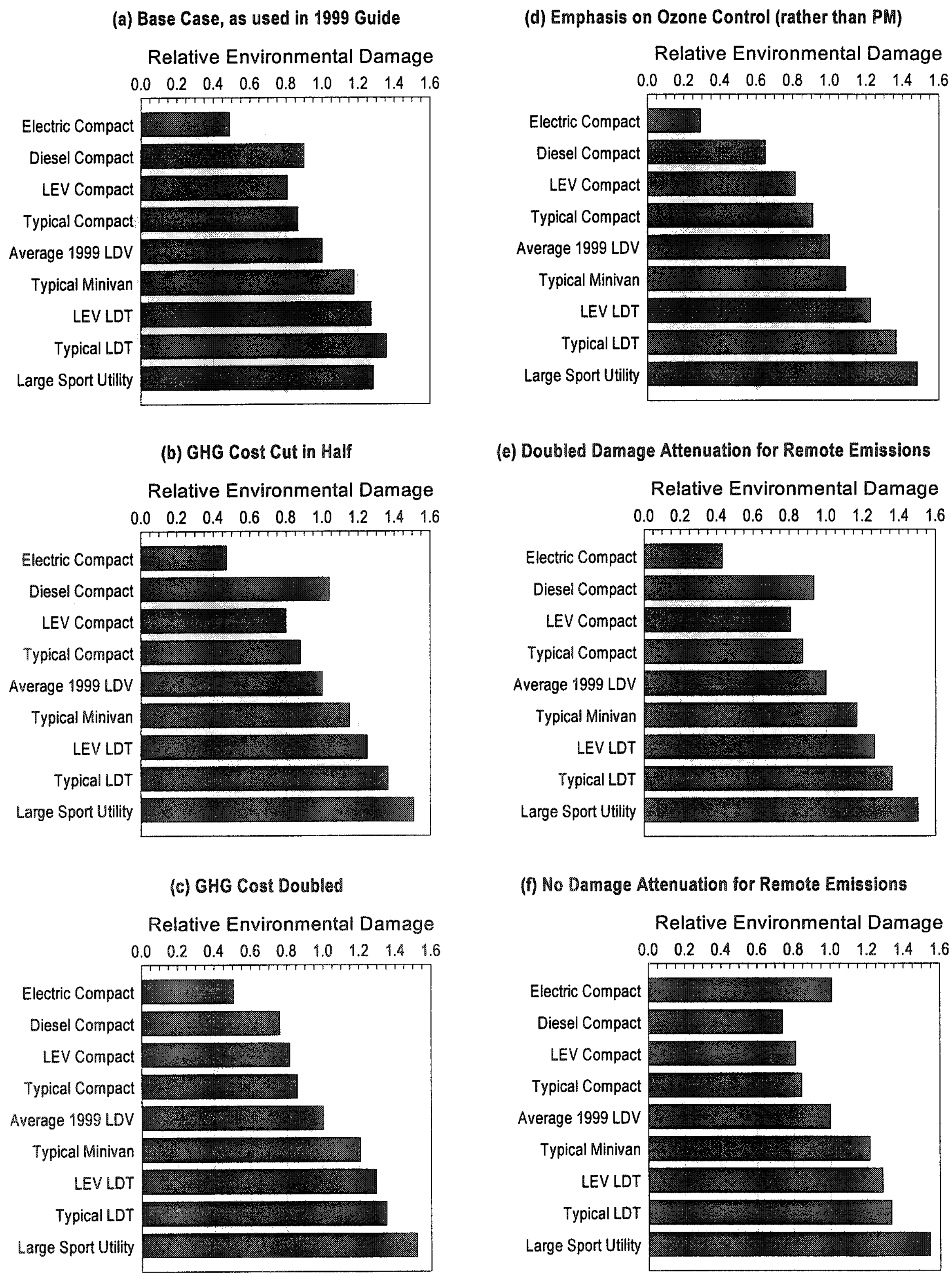

Figure 4. Green Score vs. Environmental Damage Index, with Example Vehicles

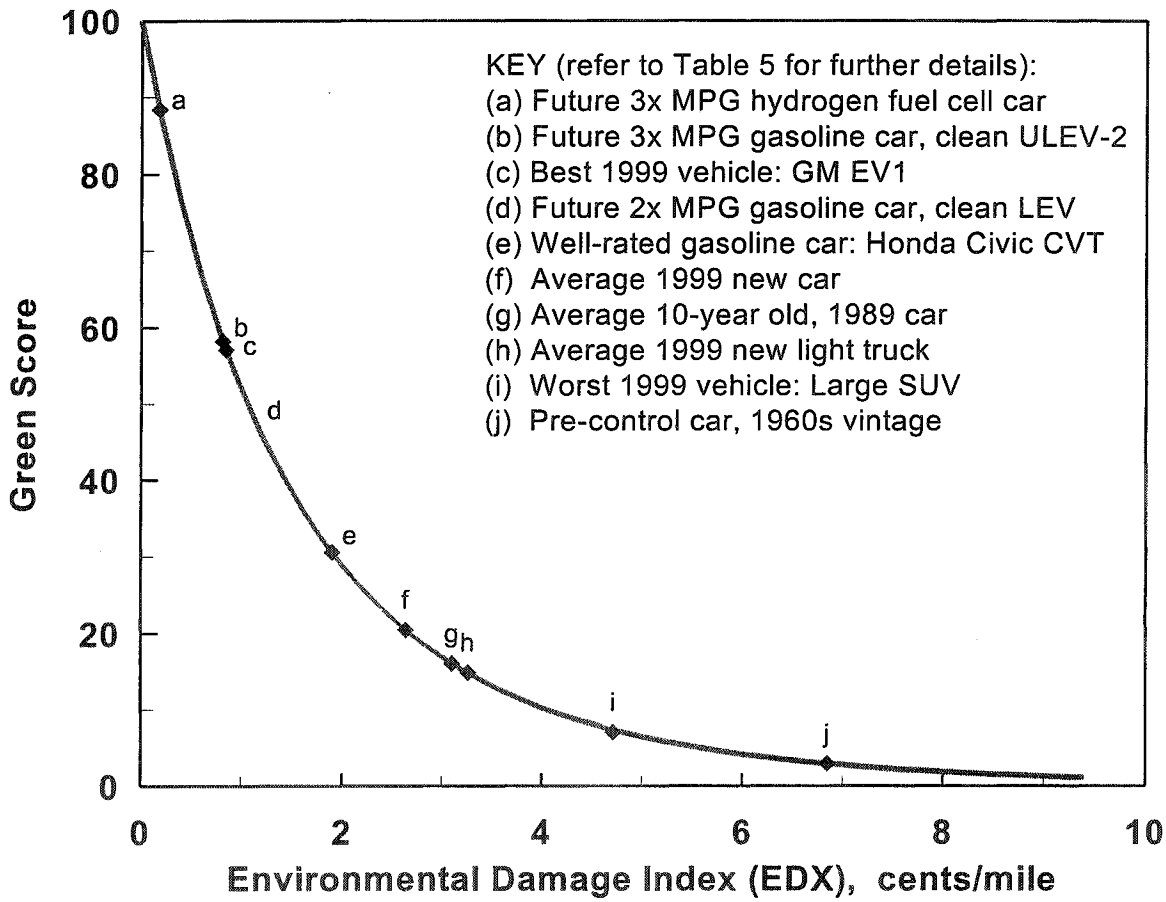

Table A1. Lifetime Average Tailpipe Emissions Estimates

This multi-part table documents our estimates of tailpipe emissions from gasoline, diesel, and compressed natural gas (CNG) vehicles according to emissions standard. All vehicles within a given light duty class and fuel type are assumed to have the same real-world emissions. Real-world (in-use) emissions performance is known to differ significantly among models that meet the same nominal standard. However, an accepted procedure does not exist for measuring and estimating such differences for the purpose of discriminating among models.

Index to subtables:

a	Tier 1 Gasoline Vehicles
b	Gasoline Transitional Low Emission Vehicles (TLEV)
c	Gasoline Low Emission Vehicles (LEV)
d	Gasoline Ultra-Low Emission Vehicles (ULEV)
e	Tier 1 Diesel Vehicles
f	Ultra-Low Emission CNG Vehicles (ULEV)
g	Super Ultra-Low Emission CNG Vehicles (SULEV)

Weight Classifications for Federally Certified Vehicles

LDV	All passenger cars
LDT1	GVW 0-6000 lb and LVW 0-3750 lb
LDT2	GVW 0-6000 lb and LVW 3751-5750 lb
LDT3	GVW 6001-8500 lb and ALVW 0-5750 lb
LDT4	GVW 6001-8500 lb and ALVW 5751-8500 lb
HDT (Class 2B)	GVW 8501-10000 lb

Weight Classifications for California Certified Vehicles

PC	All passenger cars
LDT1-CA	GVW 0-6000 lb, LVW 0-3750 lb
LDT2-CA	GVW 0-6000 lb, LVW 3751-5750 lb
MDV2-CA	GVW 6001-14000 lb, ALVW 3751-5750 lb
MDV3-CA	GVW 6001-14000 lb, ALVW 5751-8500 lb
MDV4-CA	GVW 6001-14000 lb, ALVW 8501-10000 lb

Vehicle Curb Weight (VCW) is the weight of the vehicle with all of its tanks full and components included but no passenger or luggage (load) adjustments.
Gross Vehicle Weight (GVW) is the value specified by the manufacturer as a vehicle's maximum design loaded weight.
Loaded Vehicle Weight (LVW) is the vehicle curb weight plus 300 lb. LVW = VCW + 300 lb.
Average Loaded Vehicle Weight (ALVW) is the average of the vehicle's curb weight and GVW: ALVW = (VCW + GVWR) / 2.

Note that, in contrast to Federal standards, the California light duty truck (LDT) classifications are determined strictly by loaded vehicle weight (LVW). Also, California medium duty emissions standards cover vehicles up to 10,000 LVW, including many vehicles exempt from the Federal light duty standards.

Table A1. Lifetime Average Tailpipe Emissions Estimates (cont.)

Preface

All emission factors for gasoline and diesel vehicles are scaled from basic emission rates for Tier 1 cars (LDV) shown in Table A1a and Table A1e, respectively. Tailpipe emissions of CO, HC and NOx are divided into four sources: on-cycle, off-cycle, degradation and malfunction.

We assume that on-cycle and degradation emissions are proportional to emissions standards, since they are explicitly regulated by the standards. We assume that off-cycle and malfunction emissions scale with vehicle weight (load). Emission rates for each of the light duty truck (LDT1-4) classes and heavier light trucks (HLT) are scaled up from the basic rates as described below and shown in the subtables. For the more strict California standards, emission rates are scaled down from the Federal (Tier 1) LDV and LDT rates as shown below. This method does not apply to PM emissions, which are estimated as described in the subtables.

Scaling Emissions Factors from Cars to Light Duty Trucks (gasoline)

Source of emissions	
On-cycle	Scales with ratio of LDT Std : LDV Std
Off-cycle	Scales with ratio of LDT weight : LDV weight
Degradation	Scales with ratio of LDT Std : LDV Std
Malfunction	Scales with ratio of LDT weight : LDV weight

Scaling Emissions Factors from Cars to Light Duty Trucks (diesel)

Source of emissions	
On-cycle	Scales with ratio of LDT Std : LDV Std
Off-cycle	Scales with ratio of LDT weight : LDV weight

Scaling Emissions Factors from Federal (Tier 1) to California Standards

Source of emissions	
On-cycle	Scales with ratio of CA Std : Tier 1 Std
Off-cycle	Assumed to be the same as Tier 1 estimate
Degradation	Scales with ratio of CA Std : Tier 1 Std
Malfunction	Assumed to be the same as Tier 1 estimate

Scaling Emissions Factors from LDT4s to Heavier Light Trucks (HLT) (gasoline and diesel)

Source of emissions	
On-cycle	Scales with ratio of HLT weight : LDV4 weight
Off-cycle	Scales with ratio of HLT weight : LDV4 weight
Degradation	Scales with ratio of HLT weight : LDV4 weight
Malfunction	Scales with ratio of HLT weight : LDV4 weight

Load Scaling Factors

	ITW		Ratio
LDV	3500	a	1.00
LDT1	3500	a	1.00
LDT2	4500	a	1.29
LDT3/MDV2	5275	b	1.51
LDT4/MDV3	6000	a	1.71
HLT	6300	c, d	1.05

Notes

a) Median ITW for each weight class is derived from MY1999 data provided by EPA to ACEEE
b) We assume the midpoint between LDT2 and LDT4
c) HLT weight is taken by adding the typical 300 lb increment over LDT4s determined from review of industry specifications of HLTs.
d) HLT emissions are scaled by load to LDT4 emissions. The ratio here is HLT weight/LDT4 weight.

Table A1a. Tailpipe Emissions for a Federally Certified Gasoline Vehicle (Tier 1)

Standards (a)

	CO	**NMHC**	**NOx**	**PM10** (b)
LDV	3.4	0.25	0.4	0.08
LDT1	3.4	0.25	0.4	0.08
LDT2	4.4	0.32	0.7	0.08
LDT3/MDV2	4.4	0.32	0.7	0.10 (c)
LDT4/MDV3	5.0	0.39	1.1	0.12 (c)

LDV

Source of emissions	**CO** (d)	**NMHC** (d)	**NOx** (d)	**PM10** (e)
On-cycle	2.9	0.22	0.26	
Off-cycle	2.8	0.05	0.24	
Degradation	1.8	0.14	0.30	
Malfunction	2.0	0.19	0.24	
Total Lifetime Average, g/mi	**9.5**	**0.60**	**1.04**	**0.02**
Ratio to Standard	*2.79*	*2.40*	*2.60*	*0.26*

LDT1

Load Scaling Factor	1.00		
Ratio of LDT1 : LDV Standard	1.00	1.00	1.00

Source of emissions	**CO**	**NMHC**	**NOx**	**PM10** (h)
On-cycle (f)	2.9	0.22	0.26	
Off-cycle (g)	2.8	0.05	0.24	
Degradation (f)	1.8	0.14	0.30	
Malfunction (g)	2.0	0.19	0.24	
Total Lifetime Average, g/mi	**9.5**	**0.60**	**1.04**	**0.02**
Ratio to Standard	*2.79*	*2.40*	*2.60*	*0.26*

LDT2

Load Scaling Factor	1.29		
Ratio of LDT2 : LDV Standard	1.29	1.28	1.75

Source of emissions	**CO**	**NMHC**	**NOx**	**PM10** (h)
On-cycle (f)	3.8	0.28	0.46	
Off-cycle (g)	3.6	0.06	0.31	
Degradation (f)	2.3	0.18	0.53	
Malfunction (g)	2.6	0.24	0.31	
Total Lifetime Average, g/mi	**12.3**	**0.77**	**1.60**	**0.02**
Ratio to Standard	*2.78*	*2.40*	*2.28*	*0.26*

LDT3/MDV2

Load Scaling Factor	1.51		
Ratio of LDT3 : LDV Standard	1.29	1.28	1.75

Source of emissions	**CO**	**NMHC**	**NOx**	**PM10** (i)
On-cycle (f)	3.8	0.28	0.46	
Off-cycle (g)	4.2	0.08	0.36	
Degradation (f)	2.3	0.18	0.53	
Malfunction (g)	3.0	0.29	0.36	
Total Lifetime Average, g/mi	**13.3**	**0.82**	**1.70**	**0.02**
Ratio to Standard	*3.03*	*2.57*	*2.43*	*0.21*

Table A1a (cont.)

LDT4/MDV3

Load Scaling Factor	1.71			
Ratio of LDT4 : LDV Standard	1.47	1.56	2.75	

Source of emissions	**CO**	**NMHC**	**NOx**	**PM10** (i)
On-cycle (f)	4.3	0.34	0.72	
Off-cycle (g)	4.8	0.09	0.41	
Degradation (f)	2.6	0.22	0.83	
Malfunction (g)	3.4	0.33	0.41	
Total Lifetime Average, g/mi	**15.1**	**0.97**	**2.36**	**0.03**
Ratio to Standard	*3.03*	*2.49*	*2.15*	*0.21*

HLT

Load Scaling Factor 1.05

	CO (j)	**NMHC** (j)	**NOx** (j)	**PM10** (j)
Total Lifetime Average, g/mi	**15.9**	**1.02**	**2.48**	**0.03**

Notes

a) The 50,000 mile standard is shown unless otherwise noted. Federal LDT3 and California MDV2 50,000 mile standards are identical, as are LDT4 and MDV3 standards. The useful life standards differ slightly.

b) A PM10 standard is not specified for gasoline vehicles; the diesel PM10 standard is shown.

c) For LDT3/MDV2 and LDT4/MDV3, there is no 50,000 mile standard, only a full-life, 120,000 mile standard.

d) Real-world, 100,000 mile lifetime average emissions were estimated based on the analysis of Ross et al. (1995, 1997), Hwang (1997), and updated in Ross and Wenzel (1998).

e) Delucchi 1997b (GHG model Sheet H:Cell B21) estimates gasoline vehicle in-use PM10 emissions at 0.042 g/mi, based on a review of available measurements and comparison to EPA's Particulate emissions model (PART). For our calculation procedure, we represent these emissions by applying a downward adjustment factor to a "standard" in this case taken to be the same as the diesel PM10 standard. Based on recent evaluations of PM exhaust from vehicles with 3-way catalysts, we reduce this estimate by 50%.

f) The on-cycle and degradation emission rates for LDVs are multiplied by the ratio of LDT : LDV standards to obtain LDT rates, as described in the Preface to Table A1.

g) The off-cycle and malfunction emissions rates for LDVs are multiplied by the Load Scaling Factor to obtain LDT rates, as described in the Preface to Table A1.

h) The ratio of actual to standard emissions is assumed to be the same for LDTs as for LDVs; the LDT standard is multiplied by this ratio to estimate actual emissions.

i) Since there is no 50,000 mile PM10 standard, we adjust values by the ratio of the half-life to full-life standard for LDT2s (0.08 g/mi / 0.10 g/mi).

j) Emissions rates for LDT4s are multiplied by the Load Scaling factor to get HLT emission rates as described in the Preface to Table A1.

Table A1c. Tailpipe Emissions for a Gasoline Low Emission Vehicle (LEV)

Standards (a)

	CO	NMOG	NOx	PM10 (b)
LDV	3.4	0.075	0.2	0.08
LDT1	3.4	0.075	0.2	0.08
LDT2	4.4	0.10	0.4	0.10
MDV2	4.4	0.16	0.4	0.10
MDV3	5.0	0.195	0.6	0.12

LDV

Source of emissions	CO (c)	NMOG (c)	NOx (c)	PM10 (d)
On-cycle *	2.9	0.07	0.13	
Off-cycle **	2.8	0.05	0.24	
Degradation *	1.8	0.04	0.15	
Malfunction **	2.0	0.19	0.24	
Total Lifetime Average, g/mi	**9.5**	**0.35**	**0.76**	**0.02**
Ratio to Standard	*2.79*	*4.64*	*3.80*	*0.21*

LDT1

Load Scaling Factor	1.00			
Ratio of LDT1 : LDV Standard	1.00	1.00	1.00	

Source of emissions	CO	NMOG	NOx	PM10 (g)
On-cycle (e)	2.9	0.07	0.13	
Off-cycle (f)	2.8	0.05	0.24	
Degradation (e)	1.8	0.04	0.15	
Malfunction (f)	2.0	0.19	0.24	
Total Lifetime Average, g/mi	**9.5**	**0.35**	**0.76**	**0.02**
Ratio to Standard	*2.79*	*4.64*	*3.80*	*0.21*

LDT2

Load Scaling Factor	1.29			
Ratio of LDT2 : LDV Standard	1.29	1.33	2.00	

Source of emissions	CO	NMOG	NOx	PM10 (g)
On-cycle (e)	3.8	0.09	0.26	
Off-cycle (f)	3.6	0.06	0.31	
Degradation (e)	2.3	0.06	0.30	
Malfunction (f)	2.6	0.24	0.31	
Total Lifetime Average, g/mi	**12.3**	**0.45**	**1.18**	**0.02**
Ratio to Standard	*2.78*	*4.53*	*2.94*	*0.21*

Table A1c (cont.)

MDV2

Load Scaling Factor	1.51			
Ratio of MDV2 : LDV Standard	1.29	2.13	2.00	

Source of emissions	**CO**	**NMOG**	**NOx**	**PM10** (g)
On-cycle (e)	3.8	0.14	0.26	
Off-cycle (f)	4.2	0.08	0.36	
Degradation (e)	2.3	0.09	0.30	
Malfunction (f)	3.0	0.29	0.36	
Total Lifetime Average, g/mi	**13.3**	**0.59**	**1.28**	**0.02**
Ratio to Standard	*3.03*	*3.70*	*3.21*	*0.21*

MDV3

Load Scaling Factor	1.71			
Ratio of MDV3 : LDV Standard	1.47	2.60	3.00	

Source of emissions	**CO**	**NMOG**	**NOx**	**PM10** (g)
On-cycle (e)	4.3	0.17	0.39	
Off-cycle (f)	4.8	0.09	0.41	
Degradation (e)	2.6	0.11	0.45	
Malfunction (f)	3.4	0.33	0.41	
Total Lifetime Average, g/mi	**15.1**	**0.69**	**1.66**	**0.03**
Ratio to Standard	*3.03*	*3.55*	*2.77*	*0.21*

Notes

a) The 50,000 mile standard is shown unless otherwise noted.

b) A PM10 standard is not specified for gasoline vehicles; the diesel PM10 standard is shown. For LEVs, there is no 50,000 mile standard, only a full-life, 120,000 mile standard.

c) Real-world, 100,000 mile lifetime average emissions were estimated by a procedure similar to that for Tier 1 vehicle (see Table A1a), with the following changes:
 * NMOG reduced by the ratio of LEV /Tier 1 standards of 0.30.
 NOx reduced by the ratio of LEV /Tier 1 standards of 0.50.
 ** assumed to be the same as for a Tier 1 vehicle, since the tighter standard does not explicitly address these sources of emission.
 Note that the CO standard is the same as for a Tier 1 vehicle.

d) We maintain the same ratio (0.26 for 50,000 mile standards and 0.21 for full-life standards) of actual to standard PM10 emissions as used for Tier 1 vehicles (see Notes (e,h) in Table A1a).

e) The on-cycle and degradation emission rates for LDVs are multiplied by the ratio of LDT : LDV standards to obtain LDT rates, as described in the Preface to Table A1.

f) The off-cycle and malfunction emissions rates for LDVs are multiplied by the Load Scaling Factor to obtain LDT rates, as described in the Preface to Table A1.

g) The ratio of actual to standard emissions is assumed to be the same for LDTs as for LDVs; the LDT standard is multiplied by this ratio to estimate actual emissions.

Table A1d. Tailpipe Emissions for a Gasoline Ultra-Low Emission Vehicle (ULEV)

Standards (a)

	CO	NMOG	NOx	PM10 (b)
LDV	1.7	0.04	0.2	0.04
LDT1	1.7	0.04	0.2	0.04
LDT2	2.2	0.05	0.4	0.05
MDV2	4.4	0.10	0.4	0.05
MDV3	5.0	0.117	0.6	0.06

LDV

Source of emissions	CO (c)	NMOG (c)	NOx (c)	PM10 (d)
On-cycle *	1.5	0.04	0.13	
Off-cycle **	2.8	0.05	0.24	
Degradation *	0.9	0.02	0.15	
Malfunction **	2.0	0.19	0.24	
Total Lifetime Average, g/mi	**7.2**	**0.30**	**0.76**	**0.008**
Ratio to Standard	*4.21*	*7.44*	*3.80*	*0.21*

LDT1

Load Scaling Factor	1.00			
Ratio of LDT1 : LDV Standard	1.00	1.00	1.00	

Source of emissions	CO	NMOG	NOx	PM10 (g)
On-cycle (e)	1.5	0.04	0.13	
Off-cycle (f)	2.8	0.05	0.24	
Degradation (e)	0.9	0.02	0.15	
Malfunction (f)	2.0	0.19	0.24	
Total Lifetime Average, g/mi	**7.2**	**0.30**	**0.76**	**0.008**
Ratio to Standard	*4.21*	*7.44*	*3.80*	*0.21*

LDT2

Load Scaling Factor	1.29			
Ratio of LDT2 : LDV Standard	1.29	1.25	2.00	

Source of emissions	CO	NMOG	NOx	PM10 (g)
On-cycle (e)	1.9	0.04	0.26	
Off-cycle (f)	3.6	0.06	0.31	
Degradation (e)	1.2	0.03	0.30	
Malfunction (f)	2.6	0.24	0.31	
Total Lifetime Average, g/mi	**9.2**	**0.38**	**1.18**	**0.011**
Ratio to Standard	*4.19*	*7.61*	*2.94*	*0.21*

Table A1d (cont.)

MDV2

	CO	NMOG	NOx	PM10 (g)
Load Scaling Factor	1.51			
Ratio of MDV2 : LDV Standard	2.59	2.50	2.00	
Source of emissions	**CO**	**NMOG**	**NOx**	**PM10** (g)
On-cycle (e)	3.8	0.09	0.26	
Off-cycle (f)	4.2	0.08	0.36	
Degradation (e)	2.3	0.06	0.30	
Malfunction (f)	3.0	0.29	0.36	
Total Lifetime Average, g/mi	**13.3**	**0.51**	**1.28**	**0.011**
Ratio to Standard	*3.03*	*5.06*	*3.21*	*0.21*

MDV3

	CO	NMOG	NOx	PM10 (g)
Load Scaling Factor	1.71			
Ratio of MDV3 : LDV Standard	2.94	2.93	3.00	
Source of emissions	**CO**	**NMOG**	**NOx**	**PM10** (g)
On-cycle (e)	4.3	0.10	0.39	
Off-cycle (f)	4.8	0.09	0.41	
Degradation (e)	2.6	0.07	0.45	
Malfunction (f)	3.4	0.33	0.41	
Total Lifetime Average, g/mi	**15.1**	**0.58**	**1.66**	**0.013**
Ratio to Standard	*3.03*	*4.96*	*2.77*	*0.21*

Notes

a) The 50,000 mile standard is shown unless otherwise noted.

b) A PM10 standard is not specified for gasoline vehicles; the diesel PM10 standard is shown. For ULEVs, there is no 50,000 mile standard, only a full-life, 120,000 mile standard.

c) Real-world, 100,000 mile lifetime average emissions were estimated by a procedure similar to that for Tier 1 vehicle (see Table A1a), with the following changes:
 * CO reduced by the ratio of ULEV /Tier 1 standards of 0.50.
 NMOG reduced by the ratio of ULEV /Tier 1 standards of 0.16.
 NOx reduced by the ratio of ULEV /Tier 1 standards of 0.50.
 ** assumed to be the same as for a Tier 1 vehicle, since the tighter standard does not explicitly address these sources of emission.

d) We maintain the same ratio (0.26 for 50,000 mile standards and 0.21 for full-life standards) of actual to standard PM10 emissions as used for Tier 1 vehicles (see Notes (e,h) in Table A1a).

e) The on-cycle and degradation emission rates for LDVs are multiplied by the ratio of LDT : LDV standards to obtain LDT rates, as described in the Preface to Table A1.

f) The off-cycle and malfunction emissions rates for LDVs are multiplied by the Load Scaling Factor to obtain LDT rates, as described in the Preface to Table A1.

g) The ratio of actual to standard emissions is assumed to be the same for LDTs as for LDVs; the LDT standard is multiplied by this ratio to estimate actual emissions.

Table A1e. Tailpipe Emissions for a Tier 1 Diesel Vehicle

Standards (a)

	CO	NMHC	NOx	PM10
LDV	3.4	0.25	1.0	0.08
LDT1	3.4	0.25	1.0	0.08
LDT2	4.4	0.32	0.97	0.08
LDT3/MDV2	4.4	0.32	0.98	0.10 (b)
LDT4/MDV3	5.0	0.39	1.53	0.12 (b)

LDV

Source of emissions	CO (c)	NMHC (c)	NOx (d)	PM10 (e)
On-cycle	1.05	0.34	1.12	
Off-cycle	0.30	0.10	0.44	
Total Lifetime Average, g/mi	**1.35**	**0.44**	**1.56**	**0.17**
Ratio to Standard	*0.40*	*1.76*	*1.56*	*2.10*

LDT1

Load Scaling Factor	1.00			
Ratio of LDT1 : LDV Standard	1.00	1.00	1.00	

Source of emissions	CO	NMHC	NOx	PM10 (g)
On-cycle (f)	1.1	0.34	1.12	
Off-cycle (g)	0.3	0.10	0.44	
Total Lifetime Average, g/mi	**1.4**	**0.44**	**1.56**	**0.17**
Ratio to Standard	*0.40*	*1.76*	*1.56*	*2.10*

LDT2

Load Scaling Factor	1.29			
Ratio of LDT2 : LDV Standard	1.29	1.28	0.97	

Source of emissions	CO	NMHC	NOx	PM10 (h)
On-cycle (f)	1.4	0.44	0.00	
Off-cycle (g)	0.4	0.12	0.56	
Total Lifetime Average, g/mi	**1.7**	**0.56**	**0.56**	**0.17**
Ratio to Standard	*0.40*	*1.76*	*0.58*	*2.10*

LDT3/MDV2

Load Scaling Factor	1.51			
Ratio of LDT3 : LDV Standard	1.29	1.28	0.98	

Source of emissions	CO	NMHC	NOx	PM10 (h)
On-cycle (f)	1.4	0.44	1.10	
Off-cycle (g)	0.4	0.15	0.66	
Total Lifetime Average, g/mi	**1.8**	**0.59**	**1.76**	**0.17**
Ratio to Standard	*0.41*	*1.83*	*1.79*	*1.68*

Table A1e (cont.)

LDT4/MDV3

Load Scaling Factor	1.71			
Ratio of LDT4 : LDV Standard	1.47	1.56	1.53	

Source of emissions	CO	NMHC	NOx	PM10 (h)
On-cycle (f)	1.5	0.54	1.72	
Off-cycle (g)	0.5	0.17	0.75	
Total Lifetime Average, g/mi	**2.1**	**0.70**	**2.47**	**0.20**
Ratio to Standard	*0.41*	*1.80*	*1.61*	*1.68*

HLT

Load Scaling Factor 1.05

CO (i)	NMHC (i)	NOx (i)	PM10 (i)
2.2	0.74	2.59	0.21

Notes

a) The 50,000 mile standard is shown unless otherwise noted. Federal LDT3 and California MDV2 50,000 mile standards are identical, as are LDT4 and MDV3 standards. The useful life standards differ slightly.

b) For LDT3/MDV2 and LDT4/MDV3, there is no 50,000 mile standard, only a full-life, 120,000 mile standard.

c) Estimates from Mobile 5a as shown in document AP-42, Table 5.1.1 (EPA 1996c). The apportionment of on-cycle and off-cycle emissions is from the Supplemental Test Procedure Final Rule. See note (d).

d) Derived from the Supplemental Federal Test Procedure (SFTP) Final Rule (Federal Register 1996, pp. 54871-2). The SFTP gives an emission estimate of 1.48 g/mi at 50,000 miles and 2.07 g/mi at 100,000 for NOx plus HC, of which 88% is NOx. We average the 50,000 mile and 100,000 mile estimates and apply the SFTP apportionment of 28% off-cycle and 72% on-cycle.

e) Delucchi does not estimate PM10 emissions from light-duty diesel vehicles. Wang 1996 (Table 10, p. 43) estimates the ratio of (0.12 g/mi / 0.03 g/mi) = 4 for diesel-to-gasoline PM10 emissions; we apply the ratio to the Delucchi 1997b Sheet H:cell B21) estimate of 0.042 g/mi for gasoline vehicles to obtain 0.17 g/mi PM10 for diesel LDVs.

f) The on-cycle emission rates for LDVs are multiplied by the ratio of LDT : LDV standards to obtain LDT rates, as described in the Preface to Table A1.

g) The off-cycle emissions rates for LDVs are multiplied by the Load Scaling Factor to obtain LDT rates, as described in the Preface to Table A1.

h) Diesel PM10 emissions were estimated by applying the LDV actual-to-standard ratio to the PM standard for these classes. Since there is no 50,000 mile PM standard for LDT2/MDV3 or LDT4/MDV4, we adjust values by the ratio of the half-life to full-life standard for LDT2s (0.08g/mi : 0.10 g/mi).

i) Emissions rates for LDT4s are multiplied by the Load Scaling factor to get HLT emission rates as described in the Preface to Table A1.

Table A1f. Tailpipe Emissions for a CNG Ultra-Low Emission Vehicle (ULEV)

Standards (a)

	CO	NMOG	NOx	PM10 (b)
LDV	1.7	0.04	0.2	0.04
LDT1	1.7	0.04	0.2	0.04
LDT2	2.2	0.05	0.4	0.05
MDV2	4.4	0.10	0.4	0.05
MDV3	5.0	0.117	0.6	0.06

	CO	HC	NOx	PM
LDV				
Emissions Standard, g/mi (a)	1.7	0.04	0.2	0.04 (c)
Estimated Actual Emissions, g/mi	3.0 (b)	0.08 (b)	0.38 (b)	0.004 (d)
Ratio of Actual to Standard	*1.7*	*1.88*	*1.91*	*0.10*
LDT1				
Emissions Standard, g/mi (a)	1.7	0.04	0.2	0.04 (c)
Estimated Actual Emissions, g/mi	3.0	0.08	0.38	0.004
Ratio of Actual to Standard	*1.7* (e)	*1.88* (e)	*1.91* (e)	*0.10*
LDT2				
Emissions Standard, g/mi (a)	2.2	0.05	0.4	0.04 (c)
Estimated Actual Emissions, g/mi	3.8	0.09	0.76	0.004
Ratio of Actual to Standard	*1.7* (e)	*1.88* (e)	*1.91* (e)	*0.10*
MDV2				
Emissions Standard, g/mi (a)	2.5	0.117	0.6	0.04 (c)
Estimated Actual Emissions, g/mi	4.4	0.22	1.15	0.004
Ratio of Actual to Standard	*1.7* (e)	*1.88* (e)	*1.91* (e)	*0.10*
MDV3				
Emissions Standard, g/mi (a)	2.8	0.138	0.7	0.04 (c)
Estimated Actual Emissions, g/mi	4.9	0.26	1.34	0.004
Ratio of Actual to Standard	*1.7* (e)	*1.88* (e)	*1.91* (e)	*0.10*

Notes

a) The 50,000 mile standard.
b) From Wang 1996 (GREET model spreadsheet Vehicles: E22..E25) for CNG LDVs.
c) A PM standard is not specified for CNG vehicles; the diesel PM standard is shown.
d) Delucchi 1997b (GHG Emissions model Sheet H:Cell G50) estimates 0.0085 g/mi for CNG vehicle in-use PM emissions.
Wang 1996 (GREET model Vehicles: E26) estimates 0.0001 g/mi for CNG PM emissions.
We assume the simple mean of these two estimates (0.004 g/mi) for all classes.
e) The ratio of actual to standard emissions is assumed to be the same for LDTs as it is for LDVs; the LDT standard is multiplied by this ratio to estimate actual emissions.

Table A1g. Tailpipe Emissions for a CNG Super Ultra-Low Emission Vehicle (SULEV)

Standards (a)

	CO	NMOG	NOx	PM10 (b)
MDV2	1.0	0.01	0.02	0.01
MDV3	1.0	0.01	0.02	0.01

	CO	NMOG	NOx	PM10
MDV2				
Emissions Standard, g/mi (a)	1	0.01	0.02	0.01 (c)
Estimated Actual Emissions, g/mi	1.7	0.02	0.04	0.004
Ratio of Actual to Standard	*1.7* (e)	*1.88* (e)	*1.91* (e)	*0.40*
MDV3				
Emissions Standard, g/mi (a)	1	0.01	0.02	0.01 (c)
Estimated Actual Emissions, g/mi	1.7	0.02	0.04	0.004
Ratio of Actual to Standard	*1.7* (e)	*1.88* (e)	*1.91* (e)	*0.40*

Notes

a) All SULEV standards are for 120,000 miles.

b) We assume the same ratio of actual-to-standard emissions as for CNG ULEVs as given in Table A1f, multiplying it by the lower SULEV standards.

c) A PM standard is not specified for CNG vehicles; the diesel PM standard is shown.

d) Same assumptions as for CNG ULEVs in Table A1f.

e) The ratio of actual to standard emissions is assumed to be the same for LDTs as it is for LDVs; the LDT standard is multiplied by this ratio to estimate actual emissions.

Table A2a. Fuel Consumption-Dependent Emissions Factors: Vehicle In-Use Emissions

	emission factors (a)			
	Gasoline	Diesel	CNG	
Pollutant (vehicle standard)	g/gal	g/gal	g/gge	Notes
HC evap (Tier1)	13.9	0	0	(b)
HC evap (TLEV, LEV, ULEV)	10.2	0	0	(c)
HC evap (SULEV)	0	0	0	(d)
HC evap (HDT)	20.9	0	0	(e)
SOx	1.6	2.6	0.037	(f)
CH4	4.4	0.05	45.6	(f)
N20	3.3	0.35	2.59	(f)
CO2, g/gal	8200	9890	6250	(f)
g/MJ	62.2	67.6	47.4	(g)

Notes

Emissions factors are derived from Delucchi (1997b), with spreadsheet references given in brackets [], except as otherwise noted.

(a) Gasoline and CNG values are per gallon of gasoline equivalent ("gge," 125,000 Btu/gal); diesel values are per gallon of diesel (138,700 Btu/gal).

(b) Delucchi gives 0.47g/mi for evaporative NMOG [C:B16] for a 29.5 MPG vehicle [H:B15], which implies the 13.9 g/gal value used here.

(c) The EPA and CARB evaporative emission standards are the same in g/test, but the CARB test is more stringent (EPA 1997a). Therefore we estimate evaporative emissions for CARB-certified gasoline vehicles by scaling the Delucchi-derived Tier 1 estimates downward by the ratio of CARB to Tier 1 estimates as given in Mobil 5a (EPA 1997b):

(0.28 g/mi / 0.38 g/mi)* 13.9 g/gal = 10.2 g/gal

For diesel and CNG we assume zero evaporative emissions, as in Delucchi (1997b).

(d) All 1998 SULEVs are CNG vehicles, for which we assume zero evaporative emissions.

(e) HDT eavaporative emissions are estimated as the product of the Tier 1 emissions estimate multiplied by the ratio of Tier 1: HDT evaporative standards (3.0 g/test : 2.0 g/test). The test procedures are the same for LDTs and HDTs.

(f) Emissions estimates for CH4, N2O, and CO2 were derived as follows:
For gasoline, the values assume standard (not reformulated) gasoline [H: 48-62], and converted from g/mi to g/gal using Delucchi's model vehicle assumption of 29.5 MPG. The same procedure was followed for CNG vehicles.
For diesel, since Delucchi does not estimate light duty diesel emissions, we use his heavy-duty diesel g/mi estimates [H: 87-94] and convert them to g/gal using his modeled heavy-duty diesel vehicle fuel economy of 5.9 MPG.
SOx emission factors are based on the sulfur content of the fuel, as given in Delucchi (1997b).

(g) CO2 results are also shown in terms of a common energy unit, grams per megajoule (g/MJ) (1055 MJ = 1 MBtu).

Table A2b. Fuel Consumption-Dependent Emissions Factors: Upstream Emissions from Fuel Production, Distribution, and Vehicle Refueling

Pollutant	Gasoline g/gge	Diesel g/gge	CNG g/gge	Notes	Electricity g/kWh (i)
NMOG	6.1	1.6	1.0	(a)	0.010
CH4	16.6	13.4	41.8	(b)	0.008
CO	6.3	5.1	3.8	(c)	0.095
N2O	0.18	0.11	0.05	(d)	0.027
NOx	8.5	6.4	6.9	(e)	2.031
SOx	9.9	5.6	2.0	(f)	2.114
PM10	1.0	0.7	0.5	(g)	0.070
CO2	2450	1470	1190	(h)	647

Notes

All values are from the Delucchi (1997b) GHG Model, with spreadsheet references given in brackets []. Values given in g/MBtu (grams per million Btu) were converted to g/gge (grams per gallon of gasoline equivalent) using a higher heating value of 125,000 Btu/gal for gasoline.

(a) NMOG: Table 10f [K: 224]
(b) CH4: Table 10b [K: 124]
(c) CO: Table 10d [K: 184]
(d) N2O: Table 10c [K: 154]
(e) NOx: Table 10e [K: 214]
(f) SOx: Table 10g [K: 274]
(g) PM10: Table 10h [K: 304]
(h) CO2: Table 10a [K: 94]
(i) National average generation mix, as detailed in Table A2c on the following page.

Table A2c. Emissions Factors for Electric Vehicle Recharging

Key Assumptions and Parameters:

	Fossil Fuel Resource and Technology					
	Coal	Oil	Nat. Gas Boiler	Nat. Gas Turbine	Nuclear	
Generation Mix (a)	56.5%	2.2%	7.1%	1.4%	18.6%	average net
Generation Efficiency	34.5%	34.5%	33.0%	33.0%		efficiency:
Distribution Efficiency	92.0%	92.0%	92.0%	92.0%	92.0%	31.2%

Emissions rates, g/MBtu input				
NMOG	1.36	2.30	0.64	1.92
CH4	0.91	0.85	0.13	10.89
CO	11.34	15.15	18.10	49.90
N2O	4	2	2	2
NOx	306	126	155	124
SOx	341	197	0	0
PM10	11.30	5.60	0.14	1.90
CO2 (kg/MBtu)	95.3	75.0	53.5	53.5

Resulting Estimates:

Emissions per unit of delivered power (g/MBtu)	Coal	Oil	Nat. Gas Boiler	Nat. Gas Turbine	National Average	Average g/kWh
NMOG	4.3	7.2	2.1	6.3	2.8	0.010
CH4	2.9	2.7	0.4	35.9	2.2	0.008
CO	35.7	47.7	59.6	164	27.8	0.095
N2O	12.6	6.3	6.6	6.6	7.8	0.027
NOx	964	398	511	408	595	2.031
SOx	1073	621	0.9	0.9	620	2.114
PM10	35.6	17.6	0.5	6.3	20.6	0.070
CO2 (kg/MBtu)	300	236	176	176	190	647

Nuclear power externality cost

Damage cost (c/kWh)	0.61	(b)
Generation share	18.6%	(c)
Cost (c/kWh)	0.11	

Source: Delucchi (1997b) GHG Model, Sheets D, J. DOE (1997) Electric Power Annual 1996, Vol I, table 8.

(a) National average generation mix. The remainder is from renewable sources which are assumed to have zero or negligible emissions of the pollutants considered.

(b) From Ottinger et al. (1991), "Environmental Costs of Electricity," p. 34 ("starting point" values), but counting only routine operations and decommissioning costs.

(c) From DOE (1998). Annual Energy Outlook, Table A8, p. 112.

Table A3. Emissions from Vehicle Manufacture and Assembly

(a) Vehicle composition and the energy associated with materials production
Source: DeLuchi (1991), Table P.4, for a typical light duty gasoline vehicle

Material	Content Fraction	Production Energy (Btu/lb)	------- Fraction of Production Energy by Fuel ------- Coal	Oil	*fraction of oil** *residual*	*distillate*	Natural Gas	Elec- tricity
Plain Carbon Steel	45.1%	13,315	0.59	0.06	*78.2%*	*21.8%*	0.23	0.13
Iron	14.6%	8,445	0.65	0.06	*78.2%*	*21.8%*	0.25	0.04
High Strength Steel	7.5%	20,876	0.59	0.06	*78.2%*	*21.8%*	0.23	0.13
Plastics, Composites	7.1%	61,433	0	0.28	*74.3%*	*25.7%*	0.70	0.02
Fluids, Lubricants	5.7%	0	0	0	*90.9%*	*9.1%*	0	0
Aluminium	5.0%	44,352	0.04	0.05	*50.0%*	*50.0%*	0.60	0.31
Rubber	4.3%	38,307	0.20	0.30	*78.0%*	*22.0%*	0.41	0.10
Glass	2.7%	8,408	0.02	0.18	*66.7%*	*33.3%*	0.75	0.05
Other (Lead)	2.6%	6,273	0.37	0.03	*50.0%*	*50.0%*	0.30	0.30
Copper	1.6%	46,303	0.56	0.19	*50.0%*	*50.0%*	0.13	0.11
Other Steel	1.5%	13,315	0.59	0.06	*78.2%*	*21.8%*	0.23	0.13
Stainless Steel	1.0%	22,220	0.63	0.06	*78.2%*	*21.8%*	0.20	0.11
Powdered metal	0.7%	3,926	0.03	0.38	*66.7%*	*33.3%*	0.29	0.29
Zinc die cast	0.6%	32,743	0.35	0	*50.0%*	*50.0%*	0.54	0.10
Sodium	0.0%	15,658	0.26	0.01	*63.6%*	*36.4%*	0	0.73
Titanium	0.0%	60,498	0.03	0.18	*50.0%*	*50.0%*	0.10	0.69
Sulfur	0.0%	443	0.60	0	*63.6%*	*36.4%*	0.30	0.10

*From Manufacturing Energy Consumption Survey (MECS), DOE (1991).

(b) Energy for materials production by fuel (Btu per pound of vehicle)

Material	Coal	Residual Oil	Distillate Oil	Natural Gas	Electricity
Plain Carbon Steel	3,543	282	79	1,381	781
High Strength Steel	924	73	20	360	204
Stainless Steel	140	10	3	44	24
Other Steel	118	9	3	46	26
Iron	801	58	16	308	49
Plastics, Composites	0	907	314	3,053	87
Fluids, Lubricants	0	0	0	0	0
Rubber	329	385	109	675	165
Aluminium	89	55	55	1,331	687
Titanium	0	0	0	0	0
Glass	5	27	14	170	11
Copper	415	70	70	96	81
Zinc die cast	69	0	0	106	20
Powdered metal	1	7	3	8	8
Other (Lead)	60	2	2	49	49
Sodium	0	0	0	0	0
Sulfur	0	0	0	0	0
TOTAL	6,493	1,888	689	7,629	2,193
Electricity use in vehicle assembly (use of other fuels assumed negligible)					5,000
Total embodied electricity (Btu per pound of vehicle)					7,193

Table A3. Emissions from Vehicle Manufacture and Assembly (cont'd)

(c) Emissions factors and summation of embodied emissions by fuel

FUEL (units of energy content)	energy content (a)	Btu/lb of vehicle (b)	NOx	SO2	PM10
Coal (MBtu/ton)	28	6,493			
Emissions factor, lb/ton (c)			14.4	34.2	
g/MBtu			233.28	554.04	
Embodied emissions, g/lb			1.5	3.60	
Residual oil (MBtu/gal)	0.147	1,888			
Emissions factor, lb/1000 gal (c)			42	3.254	
g/MBtu			129.31	10.02	
Embodied emissions, g/lb			0.24	0.019	
Distillate oil (MBtu/gal)	0.138	689			
Emissions factor, lb/1000 gal (c)			20	0.288	
g/MBtu			65.94	0.95	
Embodied emissions, g/lb			0.0456	0.0007	
Natural Gas (Btu/cf)	1,020	7,629			
Emissions factor, lb/Mcf (c)			555	0.6	
g/MBtu			246.81	0.27	
Embodied emissions, g/lb			1.9	0.002	
Electricity (Btu/kWh)	3,412	7,193			
Emissions factor, g/MBtu (d)			740	1200	26
Embodied emissions, g/lb			5.3	8.6	0.2
Total Embodied Emissions					
grams per pound of vehicle			9.02	12.25	0.19
grams per kilogram of vehicle			19.84	26.95	0.41
adjusted for sulfur reductions (e)			19.84	24.26	0.41
adjusted for toxics release (f)			19.84	21.83	3.64
g/mi/kg, over a 100,000 mile vehicle lifetime			1.98E-04	2.18E-04	3.64E-05

Notes

(a) Babcock and Wilcox (1978); MBtu = 10^6 Btu, cf = cubic foot.

(b) From the preceding table (Table A3b).

(c) Electric Power Annual 1994 Vol. 2, Table A.3 (DOE 1995), assuming sulfur contents of 0.9% for bituminous coal, 2.0% for residual oil, and 0.2% for distillate.

(d) Energy Innovations (1997).

(e) The SO2 estimate is reduced 10% to reflect improved SOx controls from implementation of the 1990 Clean Air Act Amendments.

(f) Derived from Keoleian et al. (1997), as described in the text.

Table A4. Summary of Fuel Properties and Greenhouse Gas Emissions Factors

	Reformulated Gasoline (a)	Diesel Fuel (b)	CNG (c)	National Average Electricity (d)
Common units	gal	gal	100 scf	kWh
Density, kg/liter	0.737	0.842	0.000716	--
Energy content (HHV), Btu/unit	120,800	138,700	100,200	3,412
Higher Heating Value, MJ/kg	45.6	45.8	52.1	--
Carbon, direct content (e)	0.842	0.858	0.722	--
Direct CO2 from combustion, g/MJ (f)	61.5	67.6	47.4	--
Direct CO2 from combustion, g/gal	7830	9890	6250	
CO2-equiv from combustion, g/MJ (g)	82.4	72.3	67.4	--
Total FFC CO2-equiv, g/MJ (h)	100.5	85.9	84.0	179.7
expressed in kgCO2-equiv per unit	12.81	12.57	8.88	0.647
ratio of FFC to direct combustion CO2	*1.63*	*1.27*	*1.77*	--

Notes

The values given here were derived from the Delucchi (1997b) GHG Emissions model, version of Nov. 20, 1997; references to spreadsheet locations are in brackets [], estimates are for calculated scenario year 2005.
The values in this table are representative estimates based on vehicles which Delucchi modeled at hypothetical fuel efficiencies, and so may not exactly match the the estimates used for our ratings calculations, which were done using other Delucchi-derived parameters for particular real-world vehicle characteristics, e.g., as in Tables 4 and A2.

(a) Reformulated gasoline (RFG) is about 1.4% less dense and has an energy content about 2% lower than the 125,000 Btu/gal value for conventional gasoline; from "Characteristics of Gasolines" section [E:A20-F25].

(b) Properties for diesel fuel from "Fuel Characteristics" section [E:A65-K71].

(c) Compressed natural gas (CNG) is measured in standard cubic feet (scf) with properties as given for pipeline natural gas at standard (atmospheric) pressure and temperature, from "Characteristics of Gases" [E: 106-133]; CNG is, of course, more dense when compressed in fuel tanks.

(d) For DOE national average generating mix (see Table A2b).

(e) Mass percentage of fuel that is carbon, kgC per kg of fuel [E:F34, H69, L127].

(f) Released by combustion in motor vehicle, excluding other combustion products [H:55] (see Table A2a).

(g) CO2-equivalent GHG emissions from vehicle, counting direct CO2 plus effects of other gases [H:C62].

(h) CO2-equivalent Full Fuel Cycle (FFC) emissions: GHG emissions from vehicle plus GHG emissions from fuel and feedstock production and distribution processes, including CO2 plus effects of other gases.

Appendix B

Vehicle Inclusion and Classification

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

Classification is important to the presentation of environmental rating information, since the market is segmented into classes and most consumers compare a given model with others in its class. Yet no classification scheme is perfect. Class boundaries based on well-defined dimensions can result in seemingly arbitrary class distinctions among vehicles that fall near the boundaries. The market is, moreover, continuously evolving. A notable class that is important today, minivans, did not even exist 15 years ago. Today's most rapidly growing segment, luxury sport utility vehicles, is a far cry from the utilitarian jeeps and work vehicles of the past. The lines between station wagons, minivans, and sport utilities can be quite fuzzy. These segments have been in flux, with emerging "hybrid" styles, such as the Subaru Forester (classified by EPA as a Special Purpose Vehicle but being similar to a Midsize Wagon with 4-wheel drive).

The starting point for our classification scheme is the one used by EPA in its data bases and as used in the annual *Fuel Economy Guide* (DOE 1998b). This publication is generally released in October of the calendar year proceeding the nominal model year; for example, DOE (1998b) is the *Model Year 1999 Fuel Economy Guide.* It defines car classes based on interior volume, with a body style distinction separating wagons from coupes and sedans, and it defines light truck classes based on body styles.

Cars

For passenger cars, we use a slight aggregation of the EPA size classes. The EPA classification is based on the sum of passenger and luggage volume, with the specific volume cut-off for each class as specified in the *Fuel Economy Guide.* We combine Minicompacts and Subcompacts into a single class which we term Subcompact. We combined Midsize Station Wagons and Large Station Wagons into a single class which we term Midsize Wagon (but there are no model year 1999 vehicles meet the EPA definition of a large station wagon). 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, dissaggregating 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 Truck, Van and 4x4 Book* (Gillis 1998) and *Consumer Reports* (1997).

Pickups. EPA classes divide pickups into Small and Standard based on Gross Vehicle Weight Ratings. These definitions lead to trucks such as the Ford Ranger and Ford F150 being classified together. To separate these clearly different market segments but still maintain a simple rating system, we classify pickups by their overall width (a specification routinely reported by manufacturers). We use the roughly bimodal distribution of pickups by width to classify pickups as either Compact (Chevrolet S-10, Ford Ranger and Dodge Dakota) or Standard (Chevrolet C1500, Ford F150, and Dodge Ram). In addition, we do not classify four-wheel drive (4WD) and two-wheel (2WD) drive pickups separately as in the EPA classification.

Vans. The *Fuel Economy Guide* divides vans into Passenger and Cargo without clear distinctions. It also has separate classes for 2WD and 4WD Special Purpose Vehicles, which incorporate many models having consumer characteristics similar to passenger vans or sport utilities. In this case, we largely abandon the EPA classifications. We again use overall width as a determinant and use the roughly bimodal distribution to classify vans as either Minivans or Large Vans. This classification is also consistent with the consumer guides. The only model that does not fit clearly into either category is the Chevrolet Astro and GMC Safari twin. Based on *The Truck, Van and 4x4 Book* and *Consumer Reports*, we classify it as a minivan. EPA classifies the Chrysler Town and Country, Dodge Caravan, Ford Windstar, Chevrolet Venture and Oldsmobile Silhouette, and Pontiac TranSport as Special Purpose Vehicles and not as vans. We classify them all as Minivans.

Sport Utility Vehicles. Most sport utility vehicles are classified by EPA as Special Purpose Vehicles (2WD or 4WD). We use a classification scheme more representative of market segments, distinguishing, for example, between vehicles such as the Chevrolet Tracker and the GMC Yukon. Again overall width provides a good determinant. The three classes (Small, Medium, and Large) used in *The Truck, Van and 4x4 Book* appear well suited for classifying sport utility vehicles. Examples of Small Utilities include the Chevrolet Tracker, Suzuki Sidekick and Toyota RAV4. Medium Utilities include the Chevrolet Blazer and Jeep Cherokee. Large Utilities, typically built on Standard Pickup frames, include the Chevrolet Suburban and Ford Expedition. We avoid a classification distinction between 4WD and 2WD, listing these drivetrain variants together within a given utility vehicle size class.

EDX Distributions by Vehicle Class and Class Ranking Cutpoints

The distributions of EDX for all cars, all light trucks, and the overall 1999 light duty fleet is given in Figure 2. Table B1 gives the EDX cutpoints used to determine the symbolic within-class rankings assigned to vehicles in the *Green Guide to Cars and Truck,* based on the criteria shown in Table 6.

Table B1. Cutpoints Used to Determine Class Rankings for 1999 Vehicles

	Class Ranking Upper Limits (EDX, ¢/mi)[a]				
Vehicle Class	Superior ✔	Above Average ▲	Average ○	Below Average ▽	Inferior ✖
Two Seaters	0.90	2.35	2.60	3.00	>3.00
Subcompacts	1.75	2.00	2.40	2.60	>2.60
Compacts	1.90	2.10	2.40	2.50	>2.50
Midsize Cars	2.10	2.30	2.50	2.70	>2.70
Large Cars	2.30	2.55	2.70	2.90	>2.90
Small Wagons	1.90	2.00	2.20	2.50	>2.50
Large Wagons	2.20	2.35	2.55	2.65	>2.65
Compact Pickups	1.40	2.50	3.20	3.30	>3.30
Standard Pickups	2.78	3.30	3.60	3.80	>3.80
Small Utilities	1.10	2.30	2.70	3.10	>3.10
Medium Utilities	2.60	2.90	3.25	3.40	>3.40
Large Utilities	2.78	3.70	4.20	4.45	>4.45
Minivans	2.78	2.90	3.10	3.25	>3.25
Large Vans	2.70	3.50	3.70	3.80	>3.80

(a) A vehicle is assigned a given class ranking if its environmental damage index (EDX) is less than the cutpoint for the ranking and, for a Superior ranking, if its EDX is also less than the overall 1999 average (2.78 ¢\mi).

Appendix C

METHODOLOGY CHANGES FROM 1998 TO 1999

A number of changes and additions to our environmental rating methodology were made in updating the 1998 version for application in the *Green Guide to Cars and Trucks: Model Year 1999*. The methodological framework used for MY1999 is the same as was used for MY1998, but we modified some assumptions and numerical parameters based on reviewer comments, and analysis of new data, and expanded the ratings to cover additional vehicles. Key changes for 1999 include:

- Revised gasoline and diesel tailpipe emission factors
- Revised emission factors for electric vehicles
- The inclusion of environmental damages from toxic releases during vehicle manufacturing
- Coverage of vehicles over 8,500 lb GVW that are not regulated as light duty trucks, but are sold and used as personal vehicles (termed Heavier Light Trucks, "HLTs")

Our method for estimating HLT fuel economy and emissions is described in the main text. Here we detail the other changes made for MY1999.

Revised Tailpipe Emissions Factors

As established for our 1998 guide, we treat regulated tailpipe emissions as depending only on the emissions standard level to which a vehicle is certified, rather than on the particular test values submitted for certification. However, in 1999 we revised the method of scaling up emissions factors for heavier vehicle classes. Reviewers had commented that the 1998 method could be improved to obtain better consistency in the treatment of various LDT classes. Last year, we simply scaled all four sources by the ratio of LDT:LDV standards to obtain estimated in-use emission rates for the LDT2 and other heavier classes. Although no specific formulations were recommended by reviewers and no new data were available covering real-world, in-use emissions for the light truck classes, physical considerations imply off-cycle and malfunctions emissions behaving in proportion to vehicle load (that is, mass). The resulting new approach is as described in the main text. On-cycle and degradation emissions scale with the ratio of LDT:LDV standards, as before.

Revised Malfunction Emissions Rates

Emissions expected to occur during emission control system (ECS) malfunction represent one of the four components into which tailpipe emissions of CO, HC, and NO_x are apportioned for purposes of estimation. Ross and Wenzel (1998) presented a new estimate for malfunction emissions, based on analysis of MY1991 - MY1993 vehicle emissions data. We adopt these new estimates of 2.0 g/mi for CO, 0.19 g/mi for HC, and 0.24 g/mi for NO_x. These estimates represent a reduction of 60% for CO, 50% for HC, and 30% for NO_x, resulting in overall LDV tailpipe emission rates that are 24%, 26%, and 10% lower, respectively, for MY1999 than for

MY1998, as shown below.

Comparison of Tier 1 gasoline LDV real-world emissions rates for MY1998 and MY1999

	grams/mile			
	CO	HC	NOx	PM_{10}
Emissions Standard	3.4	0.25	0.40	0.08
1998 real-world estimate	12.5	0.81	1.15	0.04
1999 real-world estimate	9.5	0.60	1.04	0.02
Reduction, 1999 vs. 1998	24%	26%	10%	50%

Revised PM Emissions Rates

Our MY1998 estimate for gasoline PM_{10} emissions of 0.042 g/mi for Tier 1 LDVs was derived from Delucchi 1997b, who based his estimate on available measurements and comparisons to EPA's particulate emissions model (PART). More recent data on PM emissions from vehicles with 3-way catalysts suggest that rates are significantly lower (Mark and Morey 1999, Durbin et al. 1997). However, lifetime average real-world data on PM emissions are not available. Therefore we assumed a PM_{10} emission rate half of that assumed for MY1998, for a MY1999 estimate of 0.021 g/mi for Tier 1 gasoline LDVs. As remarked below, we leave our PM_{10} emission estimate for diesel vehicles unchanged at 0.17 g/mi for LDVs. As a result, for our MY1999 ratings, diesel LDVs have a PM_{10} emissions rate 8 times higher than gasoline LDVs.

Revised Electric Vehicle Emissions Factors

Emissions associated with electric vehicles are calculated based on a vehicle's consumption rate (kWh/mile) and a set of emission factors for various pollutants (in g/kWh). The emission factors depend on a choice of generation mix for electricity production. Reviewers commented that in our MY1998 methodology, we used a marginal electricity generating mix rather than a national average mix. This approach was inconsistent with other parts of the methodology in which we used national average emissions factors. Replacing the marginal EV recharging mix from Delucchi (1997b) used for MY1998, we adopt a national average mix from DOE (1997) for MY1999. The national average mix has a higher share attributed to renewables and nuclear power than the marginal mix used in MY1998, as shown below and with details in Table A2c. The resulting electric vehicle emission factors (g/kWh) are shown in Table A2b.

Electricity Generation Mixes for Electric Vehicles

RESOURCE	COAL	OIL	NATURAL GAS	NUCLEAR	OTHER	CO2-EQUIV. g/kWh	EDX TOTAL c/kWh
MARGINAL MIX (MY1998)	64%	20%	15%	1%	0%	931	3.44
AVERAGE MIX (MY1999)	57%	2%	9%	19%	13%	655	3.15

Toxic Emissions from Manufacturing

In the 1998 version of our rating methodology, the only manufacturing-related impacts included were emissions associated with the energy consumption involved in materials production and vehicle assembly. For 1999, we expand our inclusion of manufacturing impacts to include releases of toxic pollutants as accounted in Toxic Releases Inventory (TRI) data. These data are available at the factory level for major U.S. facilities; however, the available data are not sufficient to provide even-handed coverage of all makes and models because comparable data are not available for imports and because of the complexities of the supply chain. Therefore, we maintain our aggregate approach to the manufacturing phase, and develop a toxic emissions factor that is applied to all makes and models based on mass.

Keoleian et al. (1997), p. 37, give a summary estimate of 8.9 lb of TRI releases and 15.1 lb of TRI transfers per vehicle as of 1993. We assume that transfers are an order of magnitude less damaging than releases, giving a toxic release-equivalent of 8.9+1.5 = 10.4 lb, or 4.72 kg, per vehicle. Using the 1993 average light vehicle curb weight of 1460 kg implies 3.23 g/kg, i.e., 3.23 grams of toxic emissions per kg of vehicle, representing embodied TRI impacts.

The TRI includes an extensive list of substances, many of which are hydrocarbons, but their control concerns are as much for toxicity as for ozone formation, and some are metallic compounds, including carcinogens and mutagens. Damage cost estimates for such substances are not readily available. Therefore, we treat these TRI-based emissions as if they were PM_{10} released at manufacturing sites. For our EDX calculations, we add the above estimate to the embodied PM emissions estimated as described in our 1998 methodology report. Table 2 of DeCicco and Thomas (1998b) gives an embodied emissions factor 0.41 g/kg for PM; adding 3.23 g/kg pushes the estimate up to 3.64 g/kg. This change implies a cost of $26.28/tonne of vehicle, compared to the $2.97/tonne used for manufacturing-phase PM impacts in 1998. The bottom-line manufacturing contribution to the overall EDX (counting both GHG and criteria pollutants) is then pushed up from $192/tonne to $215/tonne, a 12% increase; this change corresponds to a 25% increase in the criteria-only portion of manufacturing EDX factor. See Table 2 for details.

Other Minor Revisions

CO_2 Damage Cost. Our assumption of treating GHG emissions as being equally as damaging as traditionally regulated air pollutants implied a quasi-damage cost for CO_2 of 0.0175 $/kg for MY1998. Due to the changes in the methodology described in this document for MY1999, the criteria portion of the EDX for the average car fell slightly to 0.0171 $/kg, as shown in Table 4. This change is due to parameter changes in the methodology rather than to substantive changes in new fleet average environmental performance from MY1998 to MY1999. Therefore, we adjusted the CO_2 damage cost to 0.0171 $/kg for MY1999 to maintain an equal weighting of CO_2 and criteria pollution for determining the total EDX.

EDX-to-Green Score Conversion. We convert the EDX to a 0-100 scaled Green Score (where a higher Green Score represents a cleaner vehicle) using a gamma function. For MY1998 the average vehicle had a Green Score of 20, and to maintain that for MY1999, we adjust the gamma function "b" parameter from 6 c/mi to 5.76 c/mi. We maintain this common average since average vehicle technology is essentially unchanged from MY1998 to MY1999. Again, the somewhat lower EDX values in MY1999 reflect only technical changes in the rating system parameters rather than actual improvements in average light vehicle environmental performance in MY1999 compared to MY1998.

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