EMISSIONS OF CRITERIA POLLUTANTS, TOXIC AIR POLLUTANTS, AND GREENHOUSE GASES, FROM THE USE OF ALTERNATIVE TRANSPORTATION MODES AND FUELS

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1.0 OVERVIEW

Policy makers in transportation often make investment decisions involving hundreds of millions of dollars. Typically they evaluate a wide range of alternatives -- from expanding highway capacity to managing existing demand to building a new rail line -- with respect to a broad array of seemingly incommensurable criteria. In theory, a policy maker can evaluate alternatives by cost-benefit analysis, in which one quantifies and monetizes all of the costs and benefits to society, and picks the alternative that yields the greatest net present-value of benefits. In this report, we quantify a key component of the social-cost part of cost-benefit analysis: emissions of air pollutants from different transportation modes.

The full social cost of a transportation mode consists of two major components: 1) capital and operating costs paid for in dollars by users, and 2) all other costs that result from the use of the transportation mode but which are not paid for directly in dollars by users. Some examples of this second kind of cost are: the health effects of air pollution from the combustion of transportation fuels; damages to marine ecosystems from oil spills; Federal subsidies to the construction of mass transit systems; and the costs to society of adapting to climate changes wrought by emissions of greenhouse gases. Preliminary analyses have indicated that the dollar value of the health effects of air pollution is one of the largest of these external costs of transportation (McCubbin and Delucchi, 1995). The CEC will include the cost of air pollution in its analysis and comparison of the social cost of alternative transportation modes.

There are five steps in the estimation of the dollar value of the health effects of emissions of air pollutants: 1) estimate emissions of harmful pollutants; 2) estimate the change in air quality resulting from the emissions; 3) estimate exposure to the polluted air; 4) estimate the health effects resulting from exposure; and 5) estimate the monetary value of the health effects. *This analysis is concerned with the first of these five steps: we estimate emissions of criteria pollutants, toxic air pollutants, and greenhouse gases from alternative transportation modes.*

1.1 Transportation modes

We analyze the following five modes:

- single-occupant automobiles
- carpools and vanpools
- buses
- light-rail trains
- at-grade and underground heavy-rail systems (including commuter rail)

1.2 Fuels and propulsion systems

For private automobiles, vans, and buses, we consider several different kinds of fuels and propulsion technologies:

- methanol made from coal, natural gas, or biomass, and used in internal-combustion-engine vehicles (ICEVs) or fuel-cell electric vehicles (FCEVs)

- compressed or liquefied natural gas used in ICEVs

- ethanol made from fermentation of corn (using coal to provide process energy) or from lignocellulosic biomass, and used in ICEVs

- liquefied petroleum gases from crude oil or natural gas processing, and used in ICEVs

- electricity for battery powered vehicles, considering several conventional and advanced sources of electricity generation.

1.3 Criteria air pollutants, toxic air pollutants, and greenhouse gases

Our analysis includes emissions of all the so-called “criteria” air pollutants:

- volatile organic compounds (VOCs)

- carbon monoxide (CO)

- oxides of nitrogen (NOx)

- oxides of sulfur (SOx)

- particulate matter (PM; including small-diameter PM_{10}, in some cases)

We also estimate emissions of the toxic air pollutants for which there are reliable data: in most cases, benzene, formaldehyde, aldehydes, and 1,3-butadiene. However, in many cases there are no data on toxic emissions.

Finally, we use the model developed by DeLuchi (1991, 1992) to estimate emissions of all direct and indirect greenhouse gases:

- carbon dioxide (CO_2)

- methane (CH_4)

- nitrous oxide (N_2O)

- carbon monoxide (CO)

- non-methane hydrocarbons (NMHCs)

- nitrogen-oxides (NO_X)

We do not include emissions of chlorofluorocarbons (CFCs) because under international agreements these are being phased out. We convert mass emissions of all the non-CO2 gases to the mass amount of CO2 that would have an equivalent warming effect, using conversion factors (called "Global Warming Potentials," or GWPs). We estimate emissions from the entire fuel-production and use system.

1.4 Stages of the fuelcycle

We estimate emissions from several stages or points in the entire “lifecycle” or “fuelcycle” of a transportation mode:

- Transforming a primary resource into a finished fuel (e.g., electricity production, petroleum refining, methanol production)

- Distributing and storing liquid fuels (e.g., at petroleum bulk plants) (except that we do not include tailpipe emissions from tanker trucks)

- Using a finished fuel in vehicles or power plants

- Using, servicing, and maintaining non-revenue vehicles, highway infrastructure, and support buildings (maintenance vehicles, administrative buildings, train stations, gasoline service stations, petroleum bulk plants, highways, parking lots, and so on). We have developed original, up-to-date estimates of energy use and emissions of the motor-vehicle infrastructure.

We do not estimate emissions from the construction of vehicles, facilities, or guideways, because these are one-time emissions that cannot be added to the ongoing emissions from system operation, and because the energy-use and emission-factor data in any event are quite poor.

1.5 Energy use

Fuelcycle emissions of CO_2, emissions from power plants, emissions from petroleum refining, and emissions from other sources are a function of the amount and kind of energy consumed by cars, buses, trains, and power plants. We have modeled this energy consumption in detail, using real-world data and sophisticated models:

- We use a detailed engineering model (Ross, 1994; An and Ross, 1993; Ross and An, 1993), to calculate energy use by passenger cars and vans as a function of characteristics of the trip (average speed, maximum speed, number of stops per mile, number of cold starts, and more) and characteristics of vehicles (empty weight, number of passengers, rolling-resistance coefficients, frontal area, drag coefficient, component efficiencies, energy use by accessories, use of regenerative braking, and other factors). This model enables us to represent properly the difference between the energy use of a short trip by car to a train station, and the energy use of a longer door-to-door commute trip by car.

- We had the California Energy Commission program its Elfin electricity model to calculate the amount and mix of fuels that would be used to generate the incremental electricity consumed by electric light-rail and heavy-rail transit systems. These estimates of "marginal" electricity use are in principle more accurate than the more commonly used estimates of "average" electricity use.

- Energy use by transit stations and transit maintenance activities are actual consumption data reported to us by utility managers and accountants of transit systems in Sacramento, San Francisco, Los Angeles, San Diego, Boston, and Washington, D. C.

- Energy use by trains and buses are actual energy use data reported by transit districts to the U.S. Federal Transit Administration of the U.S. Department of Transportation.

We also have considered energy use for fuel production and other activities, relying on the work of DeLuchi et al. (1992), DeLuchi (1991), and others.

1.6 Emission factors

We used the best available models and data sources to calculate emission factors for motor vehicles, power plants, petroleum refineries, and other sources.

- We use output and equations from CARB's EMFAC emissions model, and raw data on motor-vehicle emissions at each "stage" of the driving cycle, to develop a model that calculates gram / mile emission factors for petroleum and alternative-fuel vehicle as a function of trip length, ambient temperature, number of cold starts, and other factors. This model enables us to represent properly the difference between the emissions of a short trip by car to a train station, and the emissions of a longer door-to-door commute trip by car. The EMFAC model accounts for the emission standards in effect for each model-year vehicle.

- We estimate emissions from petroleum refineries as a function of fuel input, product output, emissions from individual process areas, and other factors, using data from the California Energy Commission (1992), the U.S. Environmental Protection Agency (AP-42, 1994), the California Air Resources Board (August 1991), the Energy Information Administration, and other sources. We estimate separate emission factors for gasoline, diesel, and residual fuel-oil. For methanol and ethanol production, we reviewed and analyzed the existing literature to obtain the most reliable estimates of emissions of criteria pollutants from advanced facilities with emission controls.

- We use emission factors from the CEC's Elfin model and the U.S. EPA's emission-factor handbook (EPA, 1994) to estimate emissions from power plants. We assume that controls are used to comply with the requirements of the 1990 Clean Air Act Amendments.

- We estimate emissions of toxic air pollutants on the basis of toxic-emission inventory data supplied by the California Air Resources Board (1993), and emission factors from the EPA's emission-factor handbook (EPA, 1994) and the EPA's toxic-emissions data base.

- To calculate fuelcycle greenhouse-gas emissions, we use the year-2000 emission factors calculated by the greenhouse-gas emissions model developed by DeLuchi (1991). This model estimates CO_2-equivalent emissions of all greenhouse gases from all stages of the fuelcycle, for a wide variety of alternative fuels.

1.7 Door-to-door trips

We express the emissions results in two ways: as grams of each pollutant emitted per passenger-mile of travel by each transportation mode, and as grams of each pollutant emitted during a complete door-to-door trip involving one or two modes. We assume that single-occupant autos, carpools, and vanpools go door to door directly. However, buses and trains do not go door to door; a traveler must walk, ride a bus, or drive from his door to the bus stop or rail station. Thus, for trips by bus or train, we include emissions from the use of the mode of access to the bus or train.

We use data from the *1991 Statewide Travel Survey* (Caltrans, 1993) and other sources to model how travelers get from their home to the bus stop or train station. We use estimates by the Congressional Budget Office (1977) of the length of the mode of access and the "circuity," or extra travel distance, of all trips relative to a baseline trip by a single-occupant automobile. The length and type of access is important, because a short access trip by an automobile can generate nearly as much pollution as a much longer door-to-door trip by automobile.

1.8 Metropolitan areas

Many of the factors that affect emissions from transportation modes vary from city to city. Among these city-specific factors are: load factors for transit systems; the technical characteristics of transit systems; the typical mode of access to transit systems; average traffic speeds; average temperature; emission regulations affecting vehicles and service stations; and the maintenance characteristics of systems. Because of this variability, it is more useful to the do the analysis for individual regions or metropolitan areas, rather than for the nation as a whole. We consider six metropolitan regions in this analysis:

- San Francisco
- Sacramento
- Los Angeles
- San Diego
- Boston
- Washington, D. C.

We have used city-specific data to the extent possible. For example, we surveyed transit operators in these regions directly to find out how much energy they used to maintain and service their systems. We also have detailed cost and ridership figures for all transit systems in the United States (Urban Mass Transit Administration, Section 15 reports, annual).

We will target our analysis for the years 2000-2005. This means that we will consider vehicle and fuel technology, emission factors, and energy-intensiveness factors appropriate for the period 2000 to 2005.

1.9 Relation to the larger social-cost analysis: inputs and outputs

The emissions results produced here can be linked to both transportation and land-use models and air quality models, as part of an analysis of the social cost of transportation modes. For example, an analyst first could use a model such as MINUTP to determine how transportation and land-use policies might change regional travel patterns. Then, with some assumptions about the use of alternative fuels and technologies, the analyst could apply the emission factors estimated in this project to arrive at regional emissions. The regional emissions then could be input to an air quality model, to determine the effect of the transportation and land-use policy on regional air quality.

1.10 Factors not considered

Our results -- grams / mile for each mode, and grams / trip -- cannot by themselves be used to estimate the emissions impacts of policies that add or improve transportation services. In order to analyze properly the environmental impacts of transportation policies, one must know, in addition to per-trip emission factors, the overall effect of the policy on transportation demand. That is, one must model the net change in automobile trips, bus trips, and so on, that result from a particular policy (see section 1.8 above). Obviously, the net emissions impact of, say, a new rail line depends greatly on the proportion of projected riders that would drive versus the proportion that would ride in a carpool or vanpool versus the proportion that would take a bus versus the proportion that would not travel at all, were the rail line not built. The greater the fraction of riders that would drive alone were the new line not built, the greater the emissions impacts. We do not analysis these modal impacts in this analysis. Curry (1976) summarize several studies of the previous modes of new transit passengers.

Similarly, the actual emissions impact of, say, shifting riders from cars to transit depends on whether the riders are shifted in the peak or off-peak, and how the transit operator manages its capacity. For further discussion of the environmental effects of capacity management, see Rietveld (2002).

New transportation services also can affect the flow the of traffic indirectly. For example, buses can impede automobile traffic (Cohen et al., 1978) and thereby cause vehicles to consume more fuel and emit more greenhouse gases and CO and VOCs. We do not consider these types of effects either.

2.0 LITERATURE REVIEW

There have been very few detailed comparisons of emissions from transportation modes. However, there is a substantial body of literature on the energy use of different transportation modes. Because in most cases emissions are a function of energy use, this energy literature is relevant to our analysis. To our knowledge, though, none of the existing studies of emissions or energy use cover the range of modes, pollutants, emissions sources, and other factors considered here. The following are brief summaries of some of the more prominent studies. This review is by no means comprehensive; in particular, there are many more analyses of the energy use of different transportation systems[1].

- *Scheel (1972).* This early report estimates emissions of CO, HCs, NO_2, and SO_2 from automobiles, transit buses, commuter trains, and rail transit. The analysis does not include other pollutants, and does not include emissions from the use of energy for stations, maintenance activities, guideway or vehicle construction, emissions from upstream fuel processing, or emissions from modes of access to transit. Although the

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[1] For example, we expect that most environmental-impact analyses of new transportation projects include an analysis of energy-use impacts, if not emissions impacts. We have included only environmental impact analysis here (Westec Services, 1983).

emission and energy-use factors are out of date, some of the conclusions are directionally similar to ours.

• *Fels (1975).* An original and detailed analysis of energy required to build guideways for rail systems.

• *Curry (1976).* This study summarizes an analysis of the energy consumption and air pollution impacts of eight case studies of new or improved transit services, including new bus lines, improved bus services, new exclusive bus corridors on the Shirley Highway and on the San Bernadino Freeway, and new rail transit service in the Philadelphia-Lindenwold corridor. It appears to be the first study to have examined a broad range of factors that affect energy use and emissions. The study considered emissions from modes of access to transit, with a an explicit treatment of cold-start emissions, and estimated the impact of new transit modes on travel by other modes (i.e., distinguished former car drivers from former bus riders from new trip makers). It also presented estimates of "indirect" energy use and emissions -- from stations, maintenance activities, construction of vehicles and guideways, and upstream processing of fuel -- but did not include indirect energy and emissions in the model or final results.

• *Congressional Budget Office (1977).* This landmark study reviews theoretical and applied studies of transportation energy use, and estimates energy intensiveness, line-haul energy, modal energy, and program energy for single-occupant automobiles, average automobiles, carpools, vanpools, dial-a-ride, old heavy-rail transit, new heavy-rail transit, commuter rail, light-rail transit, and bus systems. "Energy intensiveness" is defined as propulsion energy per vehicle mile divided by the average number of occupants. "Line-haul" energy includes, in addition, the energy used by stations, maintenance activities and vehicle and guideway manufacturing. "Modal" energy is equal to line haul energy plus energy use by access modes, with accounting for the circuity of the total trip compared to an auto trip and the fraction of the trip that is devoted to access. Finally, "program" energy accounts for the overall modal split as a result of new or improved transit services. The study has been cited and debated widely, and remains the most comprehensive review of energy use by urban transportation modes.

The results of this study also are presented in Cohen (1978) and Kulash (1982). The written testimony submitted at the Senate hearing on this report contain excellent critiques of data, method, and interpretation of results (U.S. Senate, 1977).

• *Fels (1978)* . An original and detailed analysis of the operational energy requirements of the heavy rail systems in San Francisco (BART), Philadelphia (PATCO), and New York-New Jersey (PATH). The analysis includes energy used for propulsion, auxiliary and standby systems, station operation, and maintenance. Monthly utility bills for each system were the main source of data. Fels (1978) does not include "upstream" energy from production of fuels and electricity, and does not examine modes of access to transit. In an earlier paper, Fels (1975) estimated the energy requirements of making vehicles and guideways.

- *Cohen et al. (1978).* This study summarizes methods for estimating emissions from motor vehicles and energy use of urban transportation systems. With one exception, all of the data on energy use are from the CBO study (discussed above). The exception is a table of vehicle manufacturing energy and related data, from a 1976 FHWA report.

- *McCoy (1982).* McCoy summarizes data on seats per vehicle, average load, miles per gallon, and kWh per vehicle mile, for different sizes of passenger cars and buses, trolley coaches, light-rail systems in several cities, and old and new heavy rail systems in several cities. The data come from a variety of papers and reports (including Fels [1978] and the CBO [1977]) and personal communications in the 1970s. He does not present data on the energy use of stations, maintenance activities, guideway or vehicle construction, upstream fuel processing, or modes of access to transit.

- *Westec Services, Inc. (1983).* This draft Environmental Impact Statement (EIS) and Environmental Impact Report (EIR) compared the total system energy consumption of the then-proposed Los Angeles Metro Rail with the total consumption of the bus-and-car systems that it replaces. Westec used the Congressional Budget Office (1977) estimates of the amount of energy required to build and maintain cars and trucks and to build rail vehicles, and Southern California Regional Transit District (SCRTD) estimates of the amount of energy required to run and maintain the proposed Metro Rail. Guideway-construction and vehicle-manufacturing energy was annualized over an assumed 50-year life. SCRTD did estimate how much the rail system would reduce travel in automobiles and buses, but it is not clear if their estimate accounted for auto-access to the rail system.

The EIS and EIR for other rail projects have similar energy estimates.

- *Reno and Bixby (1985).* This handbook, used by transportation planners to estimate the performance of urban transportation modes, presents estimates of speed, capacity, operating costs, labor inputs, energy consumption, pollution, capital costs, and accident frequency of rail rapid transit, light rail, bus, auto, automated guideway, and pedestrian assistance systems. The report estimates emissions of CO, HCs, NO_X, SO_X, aldehydes, and PM from the generation of electricity for propulsion of rapid rail, light-rail, and commuter-rail systems. It also cites estimates of the energy requirements of stations, maintenance activities, vehicle manufacture, and guideway construction, but does not calculate the corresponding emissions. It also not include greenhouse gases or toxic air pollutants, or emissions from modes of access to transit.

- *Anderson (1988)* .Anderson derives a "transit energy equation," which includes terms for rolling resistance, aerodynamic drag, acceleration, and auxiliary energy. He summarizes baseline input data for the key variables in the equation, and then uses the equation and the input data to calculate the energy requirements of heavy rail, light rail, trolley bus, motor bus, vanpool, dial-a-ride, automobile, and personal rail modes. He does not include data on the energy use of stations, maintenance activities, guideway or vehicle construction, upstream fuel processing, or modes of access to transit. His energy use equation is conceptually similar to the one we use to calculate energy use of motor vehicles.

- *Charles River Associates (1988).* This report presents statistics on a wide variety of aspects of urban transportation demand: socioeconomic characteristics of urban areas, trip generation, trip length, mode choice and auto occupancies, temporal travel distribution, truck travel, CBD characteristics, transit usage, and highway and HOV usage. The data on transit usage include summaries of modes of access to rail transit systems in several cities.
- *Linster (1990) and Lamure (1990).* These are chapters in *Transport Policy and the Environment,* published in 1990 the European Conference of Ministers of Transport. Linster (1990) shows a matrix of environmental impacts and transportation modes in which the air-pollution / rail-transport cell is blank, but the air-pollution / road-transport cell is not, indicating that road transport but not rail transport causes air pollution. No explanation is given. Lamure (1990) provides a largely qualitative comparison of the air-pollution, energy-use, noise, and land-use impacts of rail versus road transport. He argues that "if the primary energy source is not coal or oil, then the benefits of using the railways are very considerable as regards pollution of all types" (p. 123). In support of this statement, he cites a Swedish study.
- *Hughes (1991).* Hughes reports the primary propulsion energy requirements (mJ / passenger-km) of bicycles, motorcycles, minibuses, double-decker buses, urban light rail, suburban rail, intercity rail, airplanes, diesel cars, and gasoline cars in Great Britain, for typical and maximum passenger loads. The analysis does not include the energy requirements of stations, maintenance activities, or guideway or vehicle construction, but it does account crudely for "upstream" energy used to process the end-use fuels and electricity. It does not consider modes of access to transit systems.
- *American Public Transit Association (APTA) (1991).* APTA estimates emissions of hydrocarbons, nitrogen oxides, and carbon monoxide, per passenger mile of travel, for rail transit, bus transit, vanpools, carpools, and single-person automobiles. The data are presented in the *Transit Fact Book,* an annual publication of the APTA. The analysis does not include other pollutants, and does not include emissions from the use of energy for stations, maintenance activities, guideway or vehicle construction, emissions from upstream fuel processing, or emissions from modes of access to transit. (APTA, personal communication, 1993). The underlying data are average factors for energy use, travel, and emissions in the U.S. in 1987-1988 (APTA, personal communication, 1993).
- *Blevins and Gibson (1991).* This paper compares energy use and emissions of freight trucks and trains in Canada. The authors examine four routes (where the two modes actually compete), three types of rail operation (trailer-on-flatcar, car-on-flatcar, carload), three time periods (1985, 1990, 1995), and a range of different truck and rail equipment. They estimate direct emissions of CO_2, NO_X, VOCs, CO, and PM. Emissions from trains are estimated on the basis of emission-test data; emissions from trucks are assumed to be equal to the pertinent emissions standards. CO_2 emissions are calculated on the basis of fuel use and carbon content. They do not consider SO_X, toxic pollutants, other greenhouse gases, or upstream emissions. They find that trains use 65 to 70% less fuel, emit 65 to70% less CO_2 and 30 to 50% less NO_X than do trucks.

- *Craig et al. (1991)*. This report for the California Energy Commission estimates fuelcycle energy use (BTU / vehicle mile and BTU / passenger mile) and CO_2 emissions (per vehicle mile and per passenger mile) of motor buses, heavy rail, light-rail, commuter rail, trolley buses, ferry boats, vanpools, and cable cars. The data on energy use by transit systems are from the American Public Transit Association. The analysis does not include other greenhouse gases or any criteria or toxic-air pollutants, and does not include CO_2 emissions from the use of energy for stations, maintenance activities, guideway or vehicle construction, or modes of access to transit. It does, however, incorporate a detailed and original calculation of CO_2 emissions from the upstream processing of the end-use energy used for line haul.
- *Public Transport International (1991)*. This summary of report by the Canadian Urban Transit Association assumes that shifting car drivers to transit results in a net savings of the tailpipe emissions of CO_2, NO_X, VOCs, and CO from the eliminated vehicle trips. They do not count emissions from the buses or trains themselves, or from upstream processes associated with any system, or from the modes of access to the transit stations.
- *Feber and Vyas (1992)*. The authors calculate emissions of CO, HCs, NO_X, SO_X, and CO_2 from three intercity transport options: magnetically levitated intercity trains, airplanes, and automobiles. They use a utility simulation model to calculate emissions from power plants that would supply power to maglev trains, and they use MOBILE 4.1 to calculate exhaust, evaporative, refueling, and running loss emissions from motor vehicles. Electricity consumption for the maglev systems is calculated as the sum of power required for acceleration, aerodynamic drag, electromagnetic drag, and auxiliaries. The study does not consider emissions from the use of energy for stations, maintenance activities, guideway or vehicle construction, or emissions from modes of access to transit, and does not consider upstream fuelcycle emissions, PM emissions, toxic air pollutants, or greenhouse gases other than CO_2.
- *Feitelson (1994)*. This is a qualitative discussion of the direct and indirect environmental benefits and costs of rail transport. Feitelson lists “less air pollution per unit traveled” and “energy saving” as direct environmental benefits, but does give estimates or references. Vibration, noise, visual intrusion, barriers, and community severance are listed as direct environmental costs. Feitelson does note that “direct environmental benefits of rail are dependent on its ability to divert users from more polluting transport modes” (p. 210), and discusses a qualitative “market segmentation approach” to determining competitiveness of rail transit. The indirect environmental effects are mainly those on land use. Feitelson concludes that “although rail transit may reduce emissions by concentrating peak congestion spatially and temporally along some radial corridors, it is unlikely to significantly reduce total vehicle miles driven...given current land-use trends” (p. 219).
- *Maggi (1994)*. Maggi (1994) asserts that the Linster (1990) and Lamure (1990) studies cited above “illustrate the well known fact that road traffic [in Europe] is environmentally more harmful than rail traffic...most significantly [in the case of] air

pollution" (p. 346; bracketed phrases are mine). He does not offer any other evidence in support of the assertion that the environmental superiority of rail is a "well known fact".

- *Gwilliam and Geerlings (1994).* These authors cite a 1992 study by the Commission of European Communities (CEC) that indicates that switching people from motor vehicles to other modes will reduce local air pollution, at least in the short term. I have not consulted the original CEC study.

- *LaBelle and Stuart (1995).* Labelle and Stuart (1995) estimated the air quality "implications" of diverting drivers onto Chicago's rapid-rail "Orange" line in 1994. They estimated the amount of VMT and cold starts avoided as a result of shifting riders out of cars, and the amount added as a result of Park-and-Ride access to the rail line. They did not calculate changes in emissions, or consider emissions from the rail system itself. (In Chicago, most electricity comes from nuclear power.)

- *Kolb and Wacker (1995).* These researchers estimated energy use, and emissions of CO_2, by trucks, trains, ships, and planes carrying freight in Germany. They considered specific hauling tasks and routes, and estimated line-haul energy requirements in detail. They included energy use and emissions from loading and unloading operations, from "access" trips in the case of bi-modal systems, and from the construction, maintenance and disposal of vehicles, and the construction and maintenance of infrastructure. They concluded that "it is not possible to make general recommendations for transport modes" (p. 287), and that analyses should be done case by case.

Kolb and Wacker (1995) also report the results of a "similar" study done for passenger transport. They conclude that "in most cases," public transit had lower energy consumption and CO_2 emissions than did automobiles, but that the results depended greatly on the occupancy of the transit vehicles and the automobiles. If their analysis of the energy use and CO_2 emissions by passenger transport truly is similar to their analysis of freight transport (they do not report details of their analysis of passenger transport), then they probably include in the passenger-transport analysis emissions from access to public transit, and from the construction and maintenance of vehicles and infrastructure.

Apparently, neither the freight nor the passenger analysis considered emissions of other greenhouse gases, urban air pollutants, or toxics, or emissions from the lifecycle of fuels or electricity.

- *Barth et al. (1996).* Barth et al. (1996) compared emissions of VOCs, CO, NO_X, and PM from a commute via the Metrolink rail system in Los Angeles with emissions from a door-to-door commute via automobile. In the analysis of the rail commute, the researchers estimated emissions from the access trip from home to rail station, and emissions from the diesel locomotive line-haul from Riverside to Los Angeles. The surveyed passengers on the train in order to determine the mode and length of access to the rail station. They used the EMFAC7F model to estimate emissions from automobiles used in the access trip and the door-to-door commute. Also, they used remote sensing to determine the fraction of high-emitters, which is an input to the EMFAC model.

Barth et al. (1996) found that the rail-based commute produced less VOCs and CO but more NO_X and PM than did an auto-only commute.

The study did not consider toxic air pollutants, greenhouse gases, energy use, or emissions from upstream fuelcycle processes or maintenance activities.

See Barth and Tadi (1996) for a comparison of emissions from freight haul by rail with emissions from freight haul by truck.

3.0 ENERGY USE

3.1 Energy use by light-duty cars and trucks

Emissions of greenhouse gases and upstream emissions of criteria pollutants -- but not vehicular tailpipe emissions -- are a function of fuel consumption per mile. Vehicular tailpipe emissions are not a function of fuel use because the emissions standards are in units of grams/mile, not grams per gallon or energy unit[2].

The fuel consumption of a motor vehicle is a function of a number of characteristics of the vehicle and the trip: the size of the engine, the weight of the vehicle, the aerodynamic drag of the vehicle, the average speed of the trip, the number of stops and starts, the amount of time spent idling, and so on. Ross and An (1993) (see also An and Ross, 1993, and Ross, 1994) have developed a model to estimate the fuel economy of motor vehicles as a function of the key vehicle and trip parameters. Their model allows us to estimate the difference in fuel economy (and hence greenhouse-gas emissions and upstream emissions) between, say, a 10-mile trip on the freeways and a shorter access trip on surface streets to a transit station. It also allows us to estimate more subtle but nevertheless important effects: for example, the effect of an extra stop to pick up an extra passenger, and of the extra passenger's weight, on fuel economy. Table 1 shows our use of their model, for the base-case vehicle fuels and types shown in Table 44.

The original model (Ross, 1994; Ross and An, 1993; An and Ross, 1993) was specified only for gasoline vehicles. We have expanded it to calculate the fuel consumption of methanol, ethanol, CNG, LPG, and electric vehicles. The fuel consumption of alternative-fuel vehicles is calculated relative to that of gasoline vehicles: the fuel consumption of the gasoline vehicle is multiplied first by a factor that accounts for the thermal efficiency of the alternative-fuel engine relative to that of the

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[2] Actually, there are two separate questions here: whether there is a relationship between fuel economy and emissions across different vehicles (the "design" relationship), and whether there is a relationship between fuel economy and emissions for any particular vehicle (the "use" relationship). That the emission standard is in grams/mile means that there probably is not a design relationship between fuel economy and emissions, because all vehicles must meet the same g/mile standard, regardless of fuel economy. However, the fuel economy of any individual vehicle can vary for reasons (such as extra weight) that can cause the emissions per mile to vary as well. See DeLuchi et al. (1994) for further discussion.

gasoline engine, and then by a factor that accounts for any extra weight on the alternative-fuel vehicle due to fuel storage equipment (e.g., cylinders for compressed natural gas). We also have added a regenerative braking factor, used in the case of electric vehicles. The parameters for alternative-fuel vehicles are shown in Table 2.

3.2 Fuel use by buses

All emissions per passenger mile of bus travel are a function of fuel consumption per mile. This functional relationship holds for criteria pollutants as well as for greenhouse gases, and, unlike in the case of passenger vehicles, for emissions from vehicles as well as for upstream emissions. Emissions from heavy trucks and buses, unlike emissions from passenger cars and light trucks, are regulated per unit of fuel consumption (in grams per brake-horsepower-hour); hence, a vehicle that travels more miles per unit of fuel consumed will emit fewer pollutants per mile. By contrast, emissions from passenger vehicles are regulated per mile of travel.

We calculate fuel consumption per mile for diesel buses as a function of the fuel consumption of the empty bus, the number of passengers on board and the average weight of each passenger, and the relationship between fuel consumption and weight. These data are documented in Table 3. We back-calculated the fuel consumption of empty diesel buses using data on actual fuel consumption and passenger loads for buses in Sacramento, San Francisco, Los Angeles, San Diego, Boston, and Washington, D. C.

The fuel consumption of alternative-fuel buses is calculated relative to that of diesel-fuel buses: the fuel consumption of the diesel-fuel bus is multiplied first by a factor that accounts for the thermal efficiency of the alternative-fuel engine relative to that of the diesel-fuel engine, and then by a factor that accounts for any extra weight on the alternative-fuel bus due to fuel storage equipment (e.g., cylinders for compressed natural gas). The parameters for alternative-fuel vehicles are shown in Table 2.

Source of data. The Federal Transit Administration (FTA), formerly the Urban Mass Transit Administration (UMTA), collects data on the energy use, operating expenses, revenues, and performance of transit systems in the U.S. The data are reported by the transit operators themselves, and constitute the most extensive original data series for transit systems in the U.S. UMTA/FTA sent us their complete data tables (in a spreadsheet data base) of energy use, operating expenses, and transit performance for every transit system in the U.S. from 1983 to 1990. We combined, reorganized, and condensed the data to be able to calculate the average speed, load factor (the second-to-the-last column of Tables 6 to 4), energy use per passenger-mile, and energy use per passenger capacity-mile of buses and trains in Los Angeles, San Francisco, Sacramento, San Diego, Boston, and Washington, D. C. Tables 4 to 6 show the results of this exercise for the years 1988, 1989, and 1990.

3.3 Electricity use by electric trains

Emissions per passenger-mile of train travel are a function of electricity consumption per passenger-mile of train travel. In this analysis, we assume that the electricity consumption per passenger-mile is equal to the electricity use per capacity (or place)-mile of travel divided by the load factor. The electricity use per capacity-mile is a rough indicator of the technological efficiency of the system. The load factor is equal to actual passenger-miles of travel divided by passenger-capacity-miles of travel; the higher the load factor, the lower the electricity use per passenger-mile, because each additional rider on a train increases the weight by only a small fraction and therefore increases electricity consumption per vehicle-mile by only a small fraction. (In the case of trains, we ignore this weight effect of extra passengers, and assume that electricity use per vehicle-mile is independent of the load factor.) With these inputs, we calculate first the electricity use per passenger-mile, and then the emissions per passenger-mile.

Source of data. See “Sources of data” in section 3.2 above.

Marginal mix of fuels to generate electricity for trains. We assume that trains in Sacramento use the marginal power mix in Sacramento, that trains in San Francisco use the marginal power mix in San Francisco, and so on. Our estimation of the marginal power mix in each area is discussed below.

3.4 Energy use by power plants

Energy use by power plants is discussed in section 4.2, emissions from power plants

3.5 Energy use for non-traction purposes (for transit stations, administrative buildings, and maintenance of transit systems)

Rail and bus systems consume energy to heat and light administrative buildings, run maintenance facilities, power train stations and bus stops, and fuel non-revenue vehicles (mainly maintenance vehicles and administrative vehicles). We surveyed accountants and fleet managers for transit systems in Sacramento, San Francisco, Los Angeles, San Diego, Boston, and Washington, D. C., to find out the amount and kind of energy actually consumed in recent years for these nontraction purposes -- for everything other than the operation of revenue vehicles. (These energy-use factors, multiplied by emission factors per energy unit, yield estimates of emissions as a function of use, which is what we are interested in.) The results of our surveys are presented in Table 7.

As mentioned above, we wish determine the amount and kind of energy used by transit systems for everything other than the operation of revenue vehicles. This energy use, plus energy use by revenue vehicles, should be a complete and accurate account of all energy used directly by transit systems. To be sure, however, we compared our estimates with estimates from the literature. If our survey is comprehensive and accurate, our estimates of energy use should be comparable to, and perhaps greater than, the estimates in the literature. (We say “greater than” because some of the estimates in the literature do not cover *all* non-traction uses of energy, whereas our estimates are meant to.) In Table 2, our survey estimates are expressed relative to energy use by the transit vehicles themselves, and compared with estimates in the literature of station and maintenance energy use expressed in the same way. Our estimates non-traction energy use appear to be slightly higher than the estimates of station and maintenance energy that we found in the literature (e.g., compare our estimates of BART energy). As we explained above, this actually is a good finding, because it suggests that we have not omitted important sources of energy in our surveys. (Our estimates cannot be overestimates, because they are based on actual reported energy consumption.)

3.6 Energy use by fuel production facilities

Energy use by petroleum refineries is discussed in section 4.6, emissions of greenhouse gases, and section 4.3, emissions from fuel production. Energy use by methanol and ethanol production facilities is discussed in section 4.3, emissions from fuel production.

3.7 Energy use by motor-vehicle service industries, by the maintenance and operation of highway infrastructure, and by related activities.

In section 3.5, we estimate energy use by the stations, maintenance activities, and administrative functions of transit systems -- all transit-system energy use other than that by revenue vehicles. For a symmetrical comparison, we must estimate the same sort of non-vehicular energy use attributable to motor vehicles. This turns out to be difficult, because the motor-vehicle “system” is not contained in and managed by a single entity with comprehensive records, in the way that a transit system is. Many facilities and activities related to motor-vehicle use consume energy and thus emit pollutants: petroleum bulk plants, petroleum bulk terminals, gasoline service stations, motor-vehicle manufacturing plants, parts stores, motor-vehicle dealerships, motor-vehicle maintenance and repair shops, commercial parking lots and garages, home garages, vehicle renting and leasing services, highway maintenance and police operations, highway lighting, motor-vehicle insurance offices, and offices of public motor-vehicle departments[3]. These facilities and activities use electricity, natural gas, gasoline, and diesel fuel, for power and heating. Together, this energy use is comparable to the non-traction energy use of transit systems.

The few pertinent estimates of this energy use in the literature apparently are based on studies done in the early 1970s by Oak Ridge National Laboratory. The Congressional Budget Office (CBO) (1977) cites a 1977 study by BART that estimates that automobiles consume 1,634 BTUs/vehicle-mile for “maintenance and station energy”, and a 1975 study by U.S. Office of Technology Assessment (OTA) that estimates that automobiles consume 4,930 BTUs/vehicle mile for maintenance and station energy, including energy associated with tolls, insurance, and parking. (On the basis of these studies, the CBO estimates that automobiles require 2,000 BTUs/vehicle mile for maintenance and station energy.) The BART study, and probably the OTA

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[3] We analyze emissions from petroleum refineries, and, on the transit side, emissions from electricity generation, separately. And in both the transit analysis and the motor-vehicle analysis, we do not count energy use and emissions of construction activities.

study, draw on a studies in the early 1970s by Hirst of Oak Ridge National Laboratory. Curry (1976) reproduces one of Hirst's studies. Hirst multiplies estimates of dollar-expenditures per vehicle mile of travel (VMT) by an "energy coefficient" of BTUs/$-expenditure (derived from a GNP/energy input-output analysis) to obtain an estimate of BTU/VMT. His results, as reported in Curry (1976), are:

automobile manufacture	1,300
automobile transport	300
repairs, maintenance, parts	400
tires	200
insurance	400
parking, garaging, tolls	500
taxes (highway construction)	1,000

For two reasons, the Hirst BTU/$ estimates are not suitable for us. First, we have no idea how accurate they are. Generic BTU/$ coefficients might or might not be accurate for individual industries. Second, these coefficients probably include energy used for construction, which we do not count. Consequently, we have performed our own analysis of energy use by motor-vehicle maintenance, service, administration, parts, etc. (Although we do make some $/BTU extrapolations, our $/BTU coefficients do not include construction energy.)

We use data from the Bureau of the Census on actual expenditures for energy in the relevant motor-vehicle related industries (excluding vehicle manufacturing). For most of these industries, the U.S. Bureau of the Census reports expenditures on electricity and fuel, but not actual physical quantities consumed. We divide expenditure data by our estimate of price in order to estimate physical quantities (e.g., kWh or BTUs). The calculations are documented in Tables 9 and 10.

We have extrapolated from the raw Census data to account for several sources of energy use not included in the Census data. First, we extrapolated energy use in SIC 753, maintenance and repair, to account for the relatively minor amount of maintenance and repair work done "in house" by businesses. Second, we extrapolated energy use in SIC 55, motor vehicles and motor-vehicle parts, to account for small amount of sales in other industries (such as department stores) (we also deducted energy use attributable to non-motor-vehicle related sales within SIC 55 [e.g., food sales at gasoline stations]). Third, we extrapolated energy use in SIC 752, parking, to account for energy use by free parking lots and garages. Fourth, we estimated energy use by residential (non-commercial) parking spaces. Finally, we extrapolated energy use in SICs 752 and 754 to account for energy use by insurance companies, highway maintenance activities and lighting, and public motor-vehicle agencies. Our estimates and extrapolations are documented in the notes to Tables 9 and 10.

We emphasize that we do not have much confidence in either the extrapolation from SIC 752 to account for free parking, or the extrapolation from SICs 752 and 754 to account for insurance, highway maintenance, and so on (last in the list above). As explained in note i of Table 10, to account for energy use at free parking facilities, we simply multiply energy use in SIC 752 (paid parking) by 20, which we assume is the ratio of all parking (95% of which is free) to paid parking. The problem here is that the starting datum is a very small fraction of the extrapolated total. As we explain in note i, an alternative extrapolation produces a much, much higher result. The extrapolation of energy consumption in SICs 751 and 754, to account for the energy consumption of automobile insurance companies, highway maintenance and lighting, motor-vehicle departments, and police, fire, and justice department, is done on the basis of the ratio of expenditures in all of these areas to receipts in SICs 751 and 754 (note h of Table 10). This ratio is about five. Obviously, energy use might not correlate well with dollar expenditures or receipts.

Nevertheless, our “best” estimate of total energy consumption is less than 250 BTUs/VMT -- about a order of magnitude lower than Hirst’s estimates. We believe that only a small part of this difference can be attributed to our exclusion of construction energy. Moreover, we are reasonably confident of our estimates of energy use by bulk plants, bulk terminals, service stations, parts stores, dealerships, repair facilities, and residential parking spaces. We conclude that either Hirst’s estimates are too high, or that our estimate of energy used for commercial parking, and our extrapolation of energy use in SICs 751 and 754, are too low. For example, as indicated in the notes to Table 10, an alternative data set suggests that commercial parking consumes about 50 times (!) more energy than we have estimated. Clearly, more work in this area is needed.

As indicated in Table 10, we assume that all vehicles consume (indirectly) the same amount of energy, per mile, for maintenance, service, sales, and parking. We assume that all liquid-fuel service stations (including LPG stations) consume the same amount of energy per 10^6 BTU of fuel dispensed. However, we have calculated separately the energy requirements of stations that dispense natural gas, because of the large energy requirements of compression.

4.0 EMISSION FACTORS

4.1 Emission factors for motor vehicles

Motor-vehicles emit air pollutants from four distinct sources: combustion processes in the engine, the evaporation of fuel, the wear of tires and brakes, and the kicking up of road dust. Combustion emissions (generally referred to as tailpipe or exhaust emissions) are a function of the ambient temperature, the power output of the engine, the characteristics of emission-control systems, the characteristics of fuel, the ratio of air to fuel, and other factors. Combustion processes produce all of the pollutants and greenhouse gases considered in this analysis. Evaporative emissions are a function of the characteristics of the fuel, ambient temperature, the characteristics of emission-control systems, and other factors. Evaporative emissions consist of the lighter hydrocarbons in a fuel. Tire-wear, brake-wear, and road-dust emissions are particulate matter, and are a function of vehicle size and weight and other factors.

The California Air Resources Board (CARB) and the U.S. Environmental Protection Agency (EPA) have developed computer models to estimate exhaust (combustion) and evaporative emissions from motor vehicles. We use CARB's EFMAC emissions model and other data to estimate exhaust and evaporative emissions from conventional and alternative-fuel cars, vans, and buses. We use CARB and EPA emission factors and emission-factor equations and other data to estimate PM emissions from tire wear, brake wear, and road dust.

4.1.1 NMOG, CO, and NO_X exhaust emission factors for gasoline and diesel vehicles

Modern engines and emission-control systems take a few minutes to warm up, and during this warm-up vehicles emit considerably more carbon monoxide (CO) and hydrocarbons (HCs) per mile than they do when they are fully warmed up. As a result, emissions from motor vehicles are not simply proportional to distance: a trip of 3 miles produces much more than half of the CO and HC emissions of a trip of 6 miles. This is relevant to our analysis because access trips to transit by motor vehicle typically are much shorter than straight door-to-door commute trips by auto. Figure 1 shows an idealization of emissions as a function of trip distance over the Federal Test Procedure.

The California Air Resources Board (CARB) emission-factor calculation method (CARB, *Methodology for Estimating Emissions from On-Road Motor Vehicles, Volume 1: EMFAC7F*, , 1993), accounts for the phenomenon of higher "cold-start" emissions by assuming that at the beginning of a trip there is an "extra" or "incremental" emission relative to emissions from a fully warmed-up engine. These "incremental" emissions are added to emissions from a fully-warmed up engine, which are expressed in grams/mile, to obtain total emissions from a trip. CARB's emission-factor model, EMFAC, produces incremental cold-start, incremental hot-start, and running exhaust emission factors for gasoline vehicles (GVs) and diesel vehicles.

We use CARB's emission-factor model, and data from emissions tests, to develop a model of gram-per-mile emission factors as a function of trip distance. We use this model to estimate emissions from light-duty autos and light-duty trucks (i.e., vans) fueled with reformulated gasoline, and from diesel-fueled buses. Then, using data and methods explained below, we estimate emissions from alternative-fuel vehicles relative to the gasoline or diesel-fueled baseline.

Table 11 shows EMFAC-calculated emissions from gasoline cars and trucks and diesel buses in the year 2003, under the "standard" conditions (75^{o} F, 20 mph) of the Federal Test Procedure (FTP), which provides the raw data used in the EMFAC model. Of course, in any particular city, the actual temperature and average speed will be different from the FTP standards. The EMFAC model has equations which scale the emission factors up or down for temperature and speeds other than the standard ones. We use these temperature and speed "correction" equations in this analysis to estimate emission factors at any speed and temperature.

4.1.2 NMOG, CO, and NO_X exhaust emission factors for alternative-fuel vehicles.

CARB’s EMFAC model does not calculate emission factors for alternative-fuel vehicles (AFVs). Consequently, we must develop our own set of equivalent factors for AFVs. We calculate the AFV factors from scratch, using data from the Federal Test Procedure (FTP). Specifically, we start with data on “modal” emissions (cold-transient, hot-transient, and hot-stabilized emissions) from AFVs over the FTP, and calculate emission factors for the AFVs *relative* to the modal factors for GVs, for the particular FTP results. Then, we multiply these relative emissions factors by the absolute cold-start increment, hot-start increment, and stabilized running emission factors calculated from EMFAC. Formally:

$$\mathrm{Eam} = \mathrm{Egm} \times (\mathrm{Eat}/\mathrm{Egt}) \times \mathrm{Sc} \times \mathrm{Tc} \qquad (0)$$

where:

Eam = the calculated emission factor (incremental cold start [C}, incremental hot start [H], or stabilized running exhaust [S]) for the AFV, calculated with respect to the EMFAC model result for the GV

Egm = the EMFAC-model-calculated emission factor for the GV (Table 11)

(Eat/Egt) = the ratio of the AFV emission factor [C, H, or S] to the GV emission factor [C, H, S], from a set of FTP tests (derived below)

Sc = the relevant speed correction factor (correcting for the difference between EMFAC value of Table 11 [20 mph] and the city-specific values [e.g., Table 1].) (we assume that the correction factors for AFVs are the same as those for GVs)

Tc = the relevant temperature correction factor (correcting for the difference between EMFAC value of Table 11 [75^{o} F] and the city-specific values [e.g., Table 1].) (we assume that the correction factors for AFVs are the same as those for GVs)s

the subscripts “a” and “g” refer to AFVs and GVs, respectively

the subscripts “m” and “t” refer to EMFAC model results and FTP test results, respectively

We emphasize that this method calculates the ratio of AFV to GFV modal emission factors from a particular series of emissions tests done by the ARB (Purnell, 1995; Croes, 1995; see also CARB, 1992; McNair et al., 1994) and then multiplies these ratios by the absolute GV incremental and running emission factors from EMFAC. We use this method because it explicitly relates modal emissions from AFVs to modal emissions from GVs, which is desirable because in essence we wish to analyze the effect on emissions of variously “weighting” the three modes (cold-start, hot-start, stabilized) of the drive cycle.

Formally, our analysis proceeds as follows. Keep in mind that the objective is to express the desired quantities -- the (Eat/Egt) ratios above -- in terms of the known quantities: the bag emissions from AFVs and GVs We start with the equation for calculating total FTP emissions from a gasoline vehicle:

$$0.43B1g + 0.57B3g + B2g=Fg \tag{1}$$

where:

B1g = bag-1 (cold transient) emissions from a gasoline vehicle (in Figure 1, the total area under the curve from 0 to B1)
B3g = bag-3 (hot transient) emissions from a gasoline vehicle (in Figure 1, the total area under the curve from B2 to B3)
B2g = bag-2 (hot stabilized) emissions from a gasoline vehicle (in Figure 1, the total area under the curve from B1 to B2)
Fg = total grams emitted from a gasoline vehicle during the FTP test

Now, the incremental cold-start emission is defined as the amount of emissions in bag-1 (cold transient) *in excess* of the emissions that a fully warmed up engine would have emitted during the bag-1 test (CARB, *Methodology for Estimating Emissions from On-Road Motor Vehicles, Volume 1: EMFAC7F*, , 1993; Horowitz, 1982). The emissions from a fully-warmed up engine are a function of average speed. In the FTP, bag-2 emissions (hot stabilized) divided by the distance in miles of the bag-2 test yields g/mi emissions from a fully-warmed up engine at the bag-2 speed of 16 mph. However, the bag-1 test has a higher average speed, 25.6 mph. The g/mi factor calculated from the bag-2 factor at 16 mph must be “corrected” to 25.6 mph, by use of a speed correction factor, before it can be applied to the bag-1 data for the purpose of calculating the cold-start increment. Hence, the amount that a fully warmed up engine would have emitted during the bag-1 test cycle is equal to the bag-2 g/mi factor, multiplied by the speed correction factor, multiplied by the distance of the bag-1 test in miles. Formally, then, the incremental cold-start emission is calculated as:

$$Cg = B1g - B2g \times S2 \times D1/D2 \tag{2a}$$

where:

Cg = the incremental cold-start emission from gasoline vehicles (in grams; area C1 + C2 of Figure 1)
B1g, B2g are as defined above
S2 = the speed correction factor (emissions at the bag-2 speed adjusted to what emissions would have been at the bag-1 speed)
D1= the distance of the bag-1 test (3.6 miles)
D2 = the distance of the bag-2 test (3.9 miles)

Similarly:

$$Hg = B3g - B2g \times S2 \times D1/D2 \tag{2b}$$

and

$$Sg = B2g \times S2 / D2 \quad \text{(in Figure 1, } B2g / D2 = Sg'; Sg = Sg' \times S2) \qquad (2c)$$

where:

Hg = the incremental hot-start emission from gasoline vehicles (in grams; area H1 of Figure 1)

Sg = the stabilized running exhaust-emission factor for gasoline vehicles (grams / mile)

The analogous expressions for AFVs are:

$$Ca = B1a - B2a \times S2 \times D1 / D2 \qquad (2d)$$
$$Ha = B3a - B2a \times S2 \times D1 / D2 \qquad (2e)$$
$$Sa = B2a \times S2 / D2 \qquad (2f)$$

Thus:

$$\mathbf{Ca/Cg = (B1a - B2a \times S2 \times D1/D2)/(B1g - B2g \times S2 \times D1/D2)} \qquad \mathbf{(3)}$$

$$\mathbf{Ha/Hg = (B3a - B2a \times S2 \times D1/D2)/(B3g - B2g \times S2 \times D1/D2)} \qquad \mathbf{(4)}$$

$$\mathbf{Sa/Sg = B2a/B2g} \qquad \mathbf{(5)}$$

We use equations (3) - (5) to scale EMFAC-calculated modal emission factors for gasoline vehicles[4].

Finally, note that we calculate the bag emissions (B1a, B1g, B2a, B2g, etc.) from two sets of input data: i) the *distribution* of emissions among the three bags, for each pollutant and fuel type; and ii) overall FTP emissions from AFVs *relative* to overall FTP emissions from GVs. CARB provided emissions profiles by bag for AFVs (Croes, 1995; Purnell, 1995; see also McNair et al., 1994, and CARB, 1992), which we used to calculate distribution by bag[5]. Our assumptions regarding overall FTP emissions from AFVs

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[4] The cold-start or the hot-start increment will be negative if the gram / mile emission rate in the FTP bag-1 cold-transient mode or the FTP bag-3 hot-transient mode actually is less than the gram / mile rate in the FTP bag-2 stabilized mode. A negative increment is odd but not necessary physically impossible: it implies that a vehicle emits less per mile when it is cold than when it is warmed up. We leave negative increments negative, because an increment set equal to zero (when calculated to be less than zero) will not faithfully reproduce the original FTP results from which it was derived.

[5] For ethanol there were only 8 tests on 2 vehicles -- far fewer vehicles and tests than for the other fuels (Croes,1 995). Consequently, the factors for ethanol are relatively uncertain.

relative to overall FTP from GVs are shown in Table 12.[6] The calculation is shown below.

Define the sum of bag emissions, and the bag distribution factors:

$B1g + B2g + B3g = Tg$

and

$B1g / Tg = B1g'$ (distribution factor for bag 1)
$B2g / Tg = B2g'$ (distribution factor for bag 2)
$B3g / Tg = B3g'$ (distribution factor for bag 3)

Thus we have:

$$B1g = B1g' \times Tg \tag{6a}$$
$$B2g = B2g' \times Tg \tag{6b}$$
$$B3g = B3g' \times Tg \tag{6c}$$

That is, we will calculate bag emissions given the distribution of emissions by bag, and a calculated value of Tg, total FTP emissions from the GV. The equations for AFVs are analogous. To calculate Tg:

Divide equation (1) by Tg on both sides:

$0.43B1g / Tg + 0.57B3g / Tg + B2g / Tg = Fg / Tg$
$0.43B1g' + 0.57B3g' + B2g' = Fg / Tg$

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[6] One might ask why we do not calculate AFV emission factors directly from the AFV-FTP bag emissions data (and other test data), in the way that we calculate GV emission factors from FTP test data and other data. There are two reasons. First, we do not have enough AFV emissions data to develop emission factors of the same robustness as those calculated in EMFAC for GVs. Certainly, we cannot develop speed correction factors, temperature correction factors, and so on, for AFVs. Second, AFV emission factors depend greatly on the engine design, emission-control technology, and fuel quality, all of which still are evolving. There are not enough data to develop a different set of emission factors for each of a variety of engine / control / fuel combinations, and even if there were, it would be cumbersome to use many sets of emission factors. Instead, it is simpler and probably more accurate (given the present data) to express AFV emission factors relative to GFV emission factors, and to manipulate a simple, easily obtained parameter -- the ratio of total AFV-FTP emissions to total GV-FTP emissions -- to represent the effect of different engine / control / fuel combinations. In fact, even if there were enough AFV emissions data to develop separate AFV emission factors, it still might be better to model AFV emissions *relative* to GV emissions, to ensure that the treatment of AFVs was consistent with the treatment of GVs.

One also might ask why we calculate bag emissions from data on emissions distribution by bag and overall FTP emission ratios, rather than simply use the available bag emissions data directly. We do this because it allows us to use the ratio of AFV to GV FTP-emissions -- a widely used and easily obtainable metric -- as an input variable, and allows us to manipulate the bag-distribution of the emissions separately from the total amount.

$$Tg = Fg / (0.43B1g' + 0.57B3g' + B2g') \tag{7}$$

The equation for AFVs is:

$$Ta = (Fg' \times R) / (0.43B1g' + 0.57B3g' + B2g') \tag{8}$$

where:

$$Fa / Fg = R$$

Note that when we take the ratios of Ca to Cg, Ha to Hg, and Sa to Sg, in equations (3) to (5), all of the Fg will cancel out. Thus, we do not need to know Fg, We need to know only the bag distribution factors (B1g', B2g', etc.) and the ratio of AFV-FTP emissions to GV-FTP emissions (R; Table 12).

4.1.3 Adjustment for very short trips

As noted above, in the EMFAC model the start increments (Cg or Hg) are added to stabilized running emissions (Sg) to produce total emissions over a trip. If the start increment -- the "extra" emissions with respect to stabilized running emissions -- always occurred instantaneously at the beginning of a trip, then total emissions always would be equal to stabilized emissions plus the start increment, regardless of trip length. But of course, the start increment is not instantaneous; it is "spread out" over the distance that it takes the engine and catalyst to fully warm up, which probably is on the order of 1 to 3 miles (Horowitz, 1982). A very short trip that ends before the engine is fully warmed up will not have emitted the full "incremental" start emission.

This is illustrated in Figure 1, where a trip ends at distance X, before the cold-start increment has ended (at distance W). For the trip of distance X, total emissions are equal to $Sg \times X + C1$. However, the cold start increment is equal to C1+C2 (equation (2a)), and thus EMFAC-calculated emissions would be equal to $Sg \times X + C1 + C2$ -- too high by the amount C2, which never actually is emitted.

In our model, we account for this by reducing the cold start increment to the area C1 whenever the trip distance X is less than W, which we assume is 2 miles. (We do the same for hot starts, which we assume last for 1 mile.) Formally (for cold starts):

$C1 + C2 = Cg$ (from Figure 1 and equation 2a)
$C1 = Cg - C2$

Because C2 and Cg are similar triangles:

$$C2 / Cg = ((W - X) / W)^2$$
$$C2 = Cg\ ((W - X) / W)^2$$
$$C1 = Cg - Cg\ ((W - X) / W)^2$$

Now, let:

$X / W = K$

So that we have:

$C1 = Cg - Cg\ (1-K)^2 =$
$Cg\ (1 - (1 - K)^2) =$
$Cg\ (1-(1-2K+K^2)) =$
$Cg\ (2K-K^2)$

We use the factor $2K-K^2$ to adjust the cold-start or hot-start increment whenever the trip distance X is less than warm-up distance W. We also have introduced an additional constraint: if the start increment is negative, the Y intercept (Yc in Figure 1) cannot be less than zero.

4.1.4 NMOG emissions adjusted for ozone reactivity

Although NMOG emissions can be harmful in themselves, they are more deleterious as precursors to ozone formation. Different NMOG species contribute to ozone formation at different rates (Carter, 1994). The composition of NMOG emissions, and hence the ozone forming potential of NMOG emissions, varies widely among the alternative fuels. For example, ethane emissions from CNG vehicles are relatively unreactive, whereas as formaldehyde emissions from methanol vehicles are relatively reactive. To account for this differing contribution to ozone formation, the individual NMOG emissions species can be weighted by their ozone reactivity, *relative* to the overall ozone-forming potential of the mix of NMOG emissions from the baseline gasoline vehicle. We do this here.

Specifically, we estimate CE, HE, and SE for reactivity-weighted NMOG emissions, as well as for straight mass NMOG emissions. The calculation of reactivity-weighted emission factors is identical to the calculation of NMOG mass emission factors, except that we use reactivity-weighted emissions in place of straight mass emissions. Relative reactivity adjustment factors are from Carter (1994) and McNair et al. (1994)[7]. Note that reactivity-weighted NMOG emissions from the AFVs are less than straight mass NMOG emissions, because on the whole, the constituents of AFV exhaust (and especially of CNG exhaust) are less reactive than are the constituents of GV exhaust.

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[7] We assume that the bag-by-bag distribution of reactivity-weighted emissions is the same as the as distribution of unweighted emissions.

4.1.5 Emission factors for exhaust emissions of other pollutants

CARB's EMFAC model produces estimates of PM exhaust emissions (Table 11). These emission factors are constant for all speeds and temperatures. We use them here. We use DeLuchi's (1991) estimates of emissions of the greenhouse gases CH_4 and N_2O from GVs and buses. Our assumptions for AFVs (relative to the assumptions for GVs and buses) are shown in Table 12. We estimate emissions of toxic air pollutants as a fraction of NMOG emissions, for all vehicle types (Table 13).

4.1.6 Evaporative emissions.

CARB's EMFAC model calculates four kinds of evaporative emissions: i) diurnal emissions, caused by daily temperature fluctuations; ii) hot-soak emissions, which occur just after a vehicle is turned off; iii) running loss emissions from the fuel lines and tank while the vehicle is running; and iv) resting-loss emissions from the fuel lines and tank while the vehicle is resting. We "correct" EMFAC values to the particular average daily high and low temperatures in the cities that we are analyzing. Note, though, that in the base case we do not count resting losses or diurnal losses, because these emissions do not depend on the *use* of the vehicle -- they occur when the vehicle is sitting around.

Total hot-soak evaporative emissions are a function of the number of hot-starts. For vanpools and carpools, we estimate the number of hot starts as a function of the number passengers, assuming that the vehicle idles during half of the passenger pick-ups, and is turned off and restarted for the other half.

The EMFAC-estimated evaporative emissions are shown in Table 11.

4.1.7 Emission factors for buses

The emission factors for buses are derived from the results of dynamometer tests, in which bus engines are run over a standard bus driving cycle, which includes idling. However, because diesel buses do not have catalytic converters, they do not have large incremental cold-start or hot-start emissions. Also, diesel fuel has a very low standard vapor pressure, and as result diesel buses have relatively minor evaporative emissions. CARB's EMFAC emissions model assumes that incremental cold-start, incremental hot-start emission, and evaporative-emissions from diesel buses are zero. We follow suit, and estimate running exhaust emissions only, as a function of average speed.

Alternative-fuel spark-ignition buses with catalytic converters probably do have incremental cold-start and hot-start emissions. However, many alternative-fuel buses do not have catalytic converters, and in any event it is not particularly important to model cold-start and hot-start emissions from buses because there is little reason to systematically vary trip distances by buses. We do not estimate incremental hot-start or cold-start emissions from alternative-fuel buses. Also, because we do not estimate incremental hot-start or cold-start emissions from buses, whether diesel or alternative-fuel, we do not need to estimate the number of stops and starts.

Methanol and ethanol buses will have some evaporative emissions. We estimate these emissions as a function of the amount of fuel use by buses per mile relative to fuel use by passenger cars per mile.

CARB's EMFAC model and the EPA's MOBILE model estimate emissions from buses in units of grams/mile. However, the emission standards for buses (for all HDVs, actually) are in units of grams per brake-horse-power-hour (g/bhp-hr), not grams/mile. Presumably, then, all buses are designed to meet to meet a g/bhp-hr standard. This matters because if all buses meet a given g/bhp-hr standard, then buses that have a brake fuel use (bhp-hrs/mi) different from that of the buses whose emissions constitute the EMFAC database will have different g/mi emissions. For example, buses that are more efficient than the ones used to make the EMFAC model -- that is, buses that use fewer bhp-hrs per mile -- will emit fewer grams of pollution per mile. Formally, g/mi emissions from any particular bus are equal to g/mi emissions from EMFAC buses scaled by the ratio of the brake-fuel use of the particular bus to the brake fuel use of the EMFAC buses:

$$[g/\ mi]_t = [g/\ mi]_e \times \frac{[b/\ mi]_t}{[b/\ mi]_e}$$

where:

g/mi = grams of pollutants emitted per mile of bus travel

b/mi = brake horsepower-hours of engine work used per mile of bus travel

the subscript "t" refers to buses in this analysis

the subscript "e" refers to buses used in the EMFAC model data base

We do not know the ratio of the b/mi terms per se. However, we do know, or can guess, the ratio of the fuel economies and the ratio of the thermal efficiencies. Therefore, we expand the b/mi terms:

$$[b/mi] = [f/mi] \times [b/f]$$

where:

f/mi = fuel use per mile, in horsepower-hours of fuel per mile (in effect, the inverse of fuel economy)
b/f = the thermal efficiency of the engine (brake hp-hrs of engine work per hp-hr of fuel supplied to the engine)

And we end up with:

$$[g/mi]_t = [g/mi]_e \times \frac{[f/mi]_t}{[f/mi]_e} \times \frac{[b/f]_t}{[b/f]_e}$$

We assume that the thermal efficiency of the bus engines in this analysis is close to the thermal efficiency of the bus engines in the EMFAC data base, and hence that $[b/f]_t/[b/f]_e$ is approximately equal to 1.0. The $[f/mi]_t$ are calculated using the data of Tables 2 and 3. Thus, the only problematic unknown in this equation is the fuel use, $[f/mi]_e$, of the buses used in the EMFAC database. We assume 3 mpg on diesel fuel, or about 46,200 BTUs of diesel fuel per mile.

4.1.8 Final aggregate exhaust and evaporative emissions factors

Given incremental and running exhaust emissions, and evaporative emissions, corrected for speed and temperature differences, the final total trip-average g/mile emissions factors are equal to:

$$(C \times Fc + H \times Fh + Hs \times Fh)/Dt + R + Rl + (Re + Di)/(Td \times Dt)$$

where:

C = the cold-start exhaust-emission increment, “corrected” for speed, temperature, and distance (g/cold- start)
Fc = cold-start trips divided by total trips
H = the hot-start exhaust-emission increment, “corrected for speed, temperature, and distance (g/hot start)
Fh = hot-start trips divided by total trips
Hs = evaporative hot-start emissions (g/hot start)
Dt = the distance per trip
R = corrected running exhaust emissions (g/mi)
Rl = temperature-corrected running-loss evaporative emissions (g/mi)

Re = temperature-corrected resting-loss evaporative emissions (g / day)
Di = temperature-corrected diurnal evaporative emissions (g / day)
Td = trips per day

The final corrected emission factors used in this analysis for Sacramento are shown in Table 14. The final emission factors for the other cities were derived identically, and are very similar to those shown for Sacramento. (Note that in our base-case estimates, we do not include diurnal evaporative emissions or resting loss emissions, because these emissions are not a function of vehicle use -- they occur when the vehicle is not being used.)

4.1.9 Emissions of PM_{10} from tire wear, brake wear, and re-entrained road dust.

A substantial fraction of the particulate matter suspended in the atmosphere consists of particles from motor-vehicle tires and brakes, and dust and other material that motor vehicles kick up from roads. In fact, road dust alone is by far and away the largest source of small-diameter particulate matter (of 10 microns or less diameter; PM_{10}) in the U.S., accounting for over 40% of all anthropogenic *and* biogenic PM_{10} emissions in 1994 (EPA, *National Air Pollutant Emission Trends, 1900-1994,* 1995). Because road dust is such a large source of PM_{10}, and PM_{10} probably is the most harmful major air pollutant (McCubbin and Delucchi, 1995), it is important to accurately model PM_{10} emissions attributable to motor vehicles.

Tire wear and brake wear. CARB's EMFAC7F model estimates that in the year 2003, light-duty vehicles will emit 0.2 g / mi PM from tire wear, and buses 0.66 g / mi. The EPA estimates that light-duty vehicles emit 0.002 g / mi from tire wear, and 0.0128 g / mi from brake wear (Sha et al., 1983; Energy and Environmental Analysis, 1985). (CARB does not estimate emissions from brake wear; EPA does not estimate factors for heavy-duty vehicles.) These two estimates of tire-wear emissions differ by two orders of magnitude! In the absence of better data, we use the CARB factors for tire wear, and assume that emissions from brake wear are about the same; thus we assume that LDVs emit 0.4 g / mi PM, and buses 1.2 g / mi PM, from tirewear and brakewear combined. According to the EPA (*Air Emissions Species Manual, Volume II,* 1990), 55% of tirewear and brakewear PM is PM_{10}. The final emission factors therefore are 0.22 g / mi and 0.66 g / mi (Table 11).

The rate at which tires and brakes wear out, and hence the quantity of PM_{10} emissions per mile, is approximately proportional to the mass of a vehicle. (The tire-ground frictional force, and the force required to brake a vehicle, are proportional to the mass of a vehicle.) This means that a van will emit more PM_{10} from tire wear and brake wear than will a passenger car, and that a car with three people will emit more than a car with one person. To represent this properly, we model PM_{10} emissions as being proportional to vehicle mass. We assume that the LDV emission factors of Table 11 apply to a vehicle that weighs 3125 lbs, which is approximately the average weight of passenger cars in the U.S. (Delucchi, 1995a). Then, we estimate tire-wear and brakewear emissions from any LDV in this analysis simply by scaling the factors of Table 11 by the ratio of the weight of the particular vehicle to 3125 lbs.

Road dust. Emissions of road dust per vehicle mile of travel are a function of the size and quantity of dust particles on the road, the size and speed of vehicles, and other factors. The EPA's emission factor handbook (AP-42, 1994) presents equations to calculate TSP (total suspended particulate) emissions from unpaved roads, paved urban roads, and paved industrial roads. In the equations for emissions from unpaved roads and paved industrial roads, emissions are expressed as a function of the weight of the vehicles, where the weight is raised to the 0.7 power[8]. The EPA equation for emissions from paved urban roads does not include weight or any other vehicle characteristic, but this is just a further analytical simplification. We assume that emissions from paved urban roads also are related to vehicle weight raised to the 0.7 power. (We validate this assumption below.)

Given that road dust emissions are related indirectly to vehicle weight, it follows that buses will cause much higher road dust emissions per mile than will passenger cars. We must use an equation that will represent this properly.

Furthermore, different types of roads typically contain different amounts of dust and silt. Local roads carry more silt than do freeways, and consequently a trip taken mainly on local roads will cause more PM_{10} road-dust emissions than will a trip taken on the freeway. This is relevant, of course, because a drive to the train station probably will involve relatively little freeway travel, compared to a direct drive door-to-door. The emission-factor equation also must allow us to represent this properly.

In sum, then, we need an equation that contains vehicle weight and silt loading on roads as input parameters. Towards this end we have modified the EPA's (AP-42, 1994) equation for emissions from paved industrial roads:

$$R_v = 5.057 \times l \times k \times sL_v \times \left(\frac{W_v}{2.7}\right)^{0.7} \tag{9}$$

where:

R_v = emissions of PM_{10} from paved roads, in grams per mile of travel by vehicle v

k = PM_{10} fraction of emissions of total suspended particulate matter from paved roads (0.388; EPA, AP-42, 1994)

sL_v = travel-weighted average silt loading (g/m^2) on the roads traveled by vehicle v (Table 15; see derivation below, equation (10))

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[8] In reality, emissions are determined not only by vehicle weight, but also by the number of wheels, the footprint of the vehicle, the clearance of the vehicle, the drag of the vehicle, and other characteristics. However, it is simplest to relate emissions to the most easily measured explanatory vehicle characteristic, which is weight. Thus, weight raised to the 0.7 power is a proxy for all vehicle characteristics that in theory directly determine road dust emissions.

W_v = weight of the empty baseline gasoline or diesel vehicle v (in 10^6 grams) (Tables 1and 3)[9]
l = the width of a traffic lane (3.66 meters [12 feet]; FHWA, 1993)
v = Four different vehicle and trip combinations for which emission factors are calculated (passenger cars and vans used for door-to-door direct trips; passenger cars and vans used to access transit stations; buses used for line-haul; and buses used to access transit stations)

In order to calculate an average silt loading for different types of vehicles and trips (door-to-door by car or van; access to transit by car or van; line-haul by bus; access to transit by bus), we must know the distribution of travel and the silt loading by type of road. The EPA (AP-42, 1994) summarizes 44 measurements of silt loading (expressed in g/m^2) -- on local streets, collector streets, major streets and highways, and freeways and expressways in five cities. With these data, and assumptions about the distribution of vehicle travel, we calculate an overall silt loading by multiplying the average g/m^2 silt loading for each of the four types of roads by the fraction of mileage traveled on each type of road, and summing over all road types:

$$sL_v = \sum_r sL_r \times M_{r,v} \tag{10}$$

where:

sL_v = travel-weighted average silt loading of roads traveled by vehicle type v
sL_r = average silt loading on road type r (g/m^2) (Table 15)
$M_{r,v}$ = total miles traveled on road type r divided by total miles traveled, for vehicle type v (Table 15)

Note that we assume different road/travel fractions for passenger cars versus buses, and for door-to-door trips versus access-to-transit trips.

We have checked the validity of using equation (9), which as we explained above is a modification of the EPA's equation for emissions from paved industrial roads, to

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[9] Note that we always input the empty weight of the baseline gasoline car or van or diesel bus, even if the vehicle actually being modeled for a particular trip is an alternative-fuel vehicle. This is because empty vehicle weight is a proxy for vehicle characteristics, such as size, that are the direct determinants of road dust emissions and which are more or less independent of the type of fuel and fuel storage system. A small car loaded with five passengers and two heavy CNG tanks in principle will cause less road-dust emission than a car that is larger but weighs the same because it carries only one person and no CNG tanks. The use of *empty* vehicle weight (or empty weight plus some constant payload) will properly reflect this; the use of actual loaded weights will not. (The weight of the passengers and CNG tanks will affect tire wear and brake wear; we have accounted for this here.)

estimate emissions from paved urban roads. Equation (9) is valid if it produces the same PM_{10} g/mi emission factor as does the EPA's equation for emissions from paved urban roads when the silt loading (sL) is the same in both equations and vehicle mass (W) in equation (9) is equal to the average mass implicit in the paved-urban-road equation. Presumably, the average mass implicit in the paved-urban-road equation is the travel-weighted mass of all vehicles -- light-duty, medium duty, and heavy-duty -- on urban roads. If the average vehicle mass on urban roads is assumed to be 5,000 lbs (e.g., 96% at 3200 lbs and 4% at 50000 lbs), and if the silt loading is 0.5 g/m^2, then equation (9) (in which vehicle mass is explicit) produces 3.18 g/mi, and the paved-urban-road equation (in which mass is implicit) produces 3.11 g/mi.

As a second check on our use of equation (9), we compare results from it with the EPA's (*National Air Pollutant Emission Trends, 1900-1992*, 1993) estimates of total emissions of road dust from all paved roads in 1991. We use equation (9) to estimate g/mi emission factors for each of six vehicle classes (passenger cars, motorcycles, buses, 2-axle 4-tire trucks, other single-unit trucks, and combination trucks; vehicle mass W_v in each class is taken from Delucchi [1995a], and the average silt loading sL_v for travel by each class is calculated using equation (10), with the $M_{r,v}$ estimated from FHWA [1993] data). We then multiply the g/mi emission factors by total miles of travel on paved road by each vehicle class (FHWA, 1993; we estimate that about 89% of all VMT is on paved roads), and sum over all classes. The result is 7732 tons of PM_{10} emitted from paved roads 1991. This agrees nicely with the EPA's estimate of 8150 tons of PM_{10} emitted from paved roads in 1991 (EPA, *National Air Pollutant Emission Trends, 1900-1992*, 1993).

"Track" dust from trains. Presumably, trains kick up dust from train tracks, just as cars kick up dust from roads. Unfortunately, the EPA's emission-factor handbook does not give emission factors for what we will call "track" dust. In order to estimate emissions of track dust, we assume that emissions of track dust from trains are the about the same as emissions of road dust from a bus, *per seat-mile of capacity*, given the same amount of dust on the road and the track. Our reasoning is that track-dust and road-dust emissions are related to the footprint of the vehicle, and that the number of seats per square feet on a bus is close to the number of seats per square foot of a train. Thus, to estimate track-dust emissions from trains, we specify bus values in equation (9) (e.g., vehicle weight Wv = 33,000 lbs), and then divide the resultant g/mi estimate by 70 seats/vehicle, to produce g/seat-mile. Finally, we multiply this by the fraction of track mileage that we assume is at grade (because elevated and underground tracks do not produce dust).

Obviously, our estimates of track dust are little better than educated guesses, and could be really inaccurate. We hope, though, that they are better than an estimate of zero. In the scenario analyses presented later, we include scenarios of zero track-dust emissions.

4.2 Emissions from electricity generation

Total emissions from electricity generation are a function of the kind of fuel and technology used to generate electricity, the effectiveness of any emission controls used at the power plant, and the efficiency of generation and distribution and end use. Formally, gram / passenger-mile emissions of any pollutant p attributable to electric transportation are expressed simply as:

$$E = \sum_{f} w_f \times U_{f,p} \times C_{f,p} \text{x} H_f \times T \times V$$

where:

E_p = emissions of pollutant p attributable to transportation end use (grams per passenger mile)

w_f = power from fuel / plant type f divided by power from all sources (reflecting the “marginal” or “average” generation mix)

$U_{f,p}$ = uncontrolled emissions of pollutant p from fuel / plant type f (grams / 10^6 BTU fuel input [higher heating value])

$C_{f,p}$ = effectiveness of emission control (controlled emissions / uncontrolled emission) for fuel / plant type f and pollutant p

H_f = the generating efficiency of fuel / plant type f (BTU-electricity out / BTU-fuel in, higher heating value)

T = efficiency of electricity transmission and distribution (national average of 92%, according to historical data in the EIA’s *Annual Energy Review 1993,* 1994; we assume 94% for in-state generation, and 90% for imports).

V = end use energy efficiency (BTUs delivered electricity per passenger-mile of transport)

The data for each of these variables (except T) are discussed in the following subsections.

4.2.1 “Marginal” fuels and technologies used to generate electricity

The emissions attributable to any specific activity, such as the operation of light-rail transit trains, are those that would not have occurred had the activity in question not occurred. We will call these “marginal” emissions. Marginal emissions are associated with the use of marginal fuel and generation technology at power plants -- that is, with the fuel and plants that would not have been used had the activity in question not occurred.

Which fuels and plants will be marginal depend on many factors, including: the time, location, and magnitude of the marginal electricity demand; the cost, reliability, and availability of plants and electricity on the grid; and contractual and regulatory obligations. Many such factors are included the “Elfin” model used by the California Energy Commission (CEC) and Public Utilities Commission to examine the effect of changes in electricity demand on fuel use, emissions, and other outcomes[10]. We had the CEC run Elfin to simulate the effect of a uniform 1% increase in electricity demand, nominally due to increased use of power by mass transit systems, in the PG&E (Pacific Gas & Electric), LADWP (Los Angeles Department of Water and Power), SCE (Southern California Edison), and SDG&E (San Diego Gas & Electric) service areas, in the years 1993, 1998, 2003, and 2008. (Results were not available for the Sacramento Municipal Utility District.). For each utility and year, the CEC ran a base case, without the 1% increase in demand, and then modeled the 1% increase in demand. The differences in energy use between the with and without cases are attributable to the 1% increase in electricity use[11].

Table 16 shows the fuel-use results of this analysis -- the difference between the base case and the 1%-increase-case -- for the year 2003. (The results for the other years are not reproduced here. The Elfin output for the other years can be input into our emissions model to generate results for the other years. Details are given in the accompanying User's Guide to the model.) We have used all of the Elfin results for 2003 in our analysis.

We also have projected the year-2000 marginal generation mix for transit systems in Boston, Massachusetts and Washington, D. C. (Table 20). We have included these systems in the analysis because we have energy consumption data for vehicles and buildings and stations, and because the electricity mixes are different from the mixes in California and in the nation as a whole.

4.2.2 System "average" fuels and technologies used to generate electricity

Elfin did not model the marginal generation mix for the Sacramento Municipal Utility District (SMUD). For SMUD, then, instead of the marginal mix, we use the average mix in the year 2003, as projected by the California Energy Commission (Table 19). The average mix in a given time period is represented simply by total generation by all fuel and plant types (i.e., generation for all uses, not just for particular uses of interest.)

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[10] The datasets in the Elfin model represent typical conditions in a year. To the extent that conditions in the future are not like the "typical" conditions represented in Elfin, the Elfin output will be inaccurate. Also, the Elfin datasets include the CEC's projections of the *maximum* cost, not necessarily the most likely cost, of any additional resources required by utilities. Consequently, the Elfin output are not the CEC's official projections of capacity, emissions or fuel use.

[11] Of course, in reality the extra electricity demand of a new transit system will not simply bump up demand by 1% every hour, which is what Elfin modeled. For example, rail systems use more energy during peak hours than they do after the trains stop running for the night. Unfortunately, the CEC was not able to model a change in demand hour-by-hour. We note, though, that with rail systems the difference between peak and off-peak energy use might not be as large as one might expect, because nontraction energy use (e.g., for lighting stations) is independent of passenger load (and a large fraction of total energy use), and traction energy use is only weakly related to passenger load.

Of course, there is considerable uncertainty in estimating the marginal mix of electricity consumed by any particular activity, especially when one is trying to model such small changes in electricity consumption. In light of this uncertainty, it is worthwhile to calculate emissions for all cities (not just Sacramento) on the basis of the average rather than the estimated marginal electricity mixes. Here, we perform the emissions analysis for the projected average U.S. power mix (Tables 17 and 18), and for the projected average power mix in five California Utilities (Table 19).

For PG&E, LADWP, SCE, and SDG&E, the projected average (or total overall) generation mix (Table 19) can be compared with the marginal generation mix (Table 16). For all four utilities, the marginal in-state mix uses more natural gas than does the average or total overall mix. In other words, the Elfin model indicates that utilities would tend to ramp up gas-fired plants to meet a small incremental demand due to electric transport. Given that gas-fired plants generally are not run at maximum capacity around the clock (whereas nuclear and to a lesser extent coal plants are supposed to be), this does not seem unreasonable.

4.2.3 Emissions and emission control

The Elfin model, which we use to estimate future marginal power mixes for new electric transportation systems, also projects emissions of criteria pollutants from gas-fired power plants. Table 16 shows emission factors for gas power plants in the year 2003, associated with a 1% increase in electricity demand, derived from the Elfin model. We have used these emission factors in our analysis. However, Elfin generally estimates emissions from gas-fired plants only, and the CEC's *Electricity Report* does not have any emission factors at all. Therefore, for coal, oil, and biomass--fired plants, we projected average emission factors for the year 2000, using EPA's AP-42 (1994) factors for uncontrolled emissions, and our assumptions about emissions controls (Table 22). Note that the Elfin emission factors are reasonably consistent with controlled emission factors calculated from EPA's generic emission factors. (Note too that there are few data on emission of toxic air pollutants).

4.2.4 Efficiency of power generation

As shown in Table 16, the Elfin model projects that natural-gas boilers and turbines will be around 30-33% efficient (on a higher-heating-value basis), and natural-gas combined-cycle plants around 40% efficient, in the year 2003. (The results for other years, not shown here, are similar). Elfin does not estimate the efficiency of coal, oil, or biomass-fired power plants. For these plants, we estimated national-average efficiencies from data from the Energy Information Administration (EIA) (Tables 17 and 18). The EIA-based efficiencies also are around 30-33% for most conventional generation technologies.

4.2.5 Summary of use of data

With the Elfin, California-average, and national-average projections described above, we calculated grams of pollutant emissions per kWh of electricity delivered in

Sacramento, San Francisco, Los Angeles, and San Diego (Table 24; the use of the various datasets is summarized in the note to Table 24). We use these emission factors to calculate emissions per passenger mile from the use of electric trains and electric vehicles, and emissions from petroleum refineries and alternative-fuel production plants.

4.3 Emissions from the production of liquid fuels

4.3.1 Emissions from petroleum refining

We have estimated emissions of criteria pollutants from petroleum refineries per gallon of gasoline, per gallon of diesel fuel, and per gallon of residual fuel oil produced. We have included emissions from refinery process areas, such as catalytic crackers, and from the generation of purchased electricity, as well as from the combustion of fuel (mainly refinery gas and natural gas) to raise heat. We started with CARB's (1991) estimate of emissions from refineries in 1989, allocated the emissions to different fuels (DeLuchi et al., 1992), and projected changes in emission controls by the year 2000. The assumptions and results of the analysis are presented in Table 25.

4.3.2 Emissions from the production of methanol and ethanol

Our analysis includes emissions of criteria air pollutants from facilities that produce methanol or ethanol transportation fuels. We estimate emissions for six different combinations of feedstocks and production processes: methanol from natural gas, methanol from coal, methanol from wood, ethanol from corn using coal to provide heat, ethanol from corn using biomass to provide heat, and ethanol from wood. In all cases we include emissions from the generation of bought electricity as well as on-site emissions.

Table 27 shows our calculated emissions from the six different kinds of methanol and ethanol plants, in grams per gallon of output, including emissions from electricity generation. It also shows weighted average emissions for a combination of different methanol plants and a combination of different ethanol plants.

When considering our estimates, keep in mind that emission factors for fuel production processes are a function of the specific technologies used, the operating conditions of the plant, and the type of emission control systems used. The emissions estimates of Table 27 might not apply to technologies different from those characterized in the original data sources that we used, or even to the same technologies or even plants under different conditions. Along these lines, we suspect that some of the seemingly high emission factors of Table 27 (e.g., for NMHC emissions from ethanol production) probably are not reliable.

4.3.3 Emissions from storage, distribution, transfer, and dispensing of liquid fuels.

We also estimates emissions of NMOG from spillage, leakage, evaporation, and vapor displacement from storage tanks, tanker trucks, and gasoline stations. For gasoline, we use the estimates of DeLuchi et al. (1992), who estimated emissions as a function of fuel characteristics, ambient temperature, storage and transfer techniques, the effectiveness and extent of emission controls, and other factors. Their analysis was targeted to the year 2000. For methanol and ethanol, we use DeLuchi's (1991, 1993) assumptions regarding g/gal emissions relative to g/gal emissions associated with gasoline. The results of this analysis are shown in Table 28.

4.3.4 Emissions from the generation of electricity used to compress natural gas.

Emissions from the generation of electricity used to compress natural gas are counted as emissions from service stations. The electricity consumption of CNG stations is shown in Table 10. This electricity-use factor is multiplied by the appropriate metropolitan-area g/kWh emission factor (Tables 22 and 24).

4.4 Emission factors for natural gas and diesel-fuel use by buildings

We assume that the natural gas and diesel fuel used in buildings is used in residential furnaces or similar combustors. The emission factors for these devices are shown and documented in Table 29.

4.5 Emissions factors for toxic air pollutants

Toxic air pollutants are released from fuel combustion and solvent use, at virtually all stages of all fuelcycles. The California Air Resources Board (1993) provided us with estimates of emissions of toxic air pollutants in California in 1989 from all industries related to the production and use of fuels and vehicles. These data, presented in Table 12, can be used to estimate aggregate toxic emission factors: total emissions in a particular industry divided by some measure of output from or activity the industry. We have done this to calculate toxic emission factors for the petroleum-refining industry in California (Table 26). For electricity generation, we use the EPA's SPECIATE and XATEF (toxic air pollutants) databases to determine the amount and kind of toxic air pollution emissions.

4.6 Emissions of Greenhouse gases

To estimate emissions of greenhouse gases from automobiles, buses, power plants, and all other activities , we used results from the detailed greenhouse-gas emissions model developed by DeLuchi (1991, 1993), with key input variables set at their year-2000 values. The model includes emissions from the recovery and transport of primary energy feedstocks, the production of fuels from feedstocks, the distribution of fuels to end users, the end use of fuels in vehicles, the servicing and maintenance of transport modes, the building of major energy facilities (in the cases where the emissions were likely to be important), and the manufacture of materials for motor vehicles and the assembly of motor vehicles. (We will refer to all these stages together as a "fuel cycle".) It includes emissions of CO_2, CH_4, N_2O, CO, non-methane organic compounds (NMOCs), and oxides of nitrogen (NO_X).

Table 31 shows the greenhouse-gas emission factors output from the DeLuchi (1991) model. The factors are in grams of CO_2-equivalent emissions from the fuel-cycle, per million BTU of energy delivered to end users. These factors do not include emissions from the actual end-use of fuels; these emissions are calculated separately in the transit emissions model.

Implicit in our calculation of fuelcycle emissions of greenhouse gases are two assumptions: first, that a change of X gallons of demand for fuel F causes a change of X gallons of refinery output of F and a change in production of crude oil equal to the amount required to produce X gallons of F; and second, that emissions from U.S. producers and refiners are representative of the emissions from all of the producers and refiners affected by changes in U.S. transportation demand. Neither assumption is strictly correct, because price changes affect petroleum demand in nontransportation sectors, and because oil, fuels, and vehicles are produced and traded in a world market. We suspect but do not demonstrate that the error introduced by failing to account for the effect on prices and consumption in nontransportation sectors is relatively small. We are more confident that the second assumption is reasonable, because a change in U.S. demand likely will affect U.S. refiners mainly, and because in any case the energy intensity and emissions of oil production and refining in other countries is similar to that in the U.S. (Also, recall that in the case of global warming, the location of the emissions does not matter much.)

4.6.1 California-specific values.

DeLuchi's (1991) model comes with all the variables set at projected U.S. national-average values for the year 2000. Ideally, we would have re-specified all of the variables for California conditions, but this would have been a lot of work with little return, because there are many variables and for most of them California values are close to national values. Instead, we acquired and entered California-specific data for a few important variables, pertaining to energy use by oil refineries, and mode of shipment of crude oil to refineries. We compared the amount and kind of energy used by refineries in California with the amount and kind used nationally, and the modes of shipments of oil to California refineries with the modes of shipment of oil to refineries nationally (EIA, unpublished state-level data, 1993; EIA, *Petroleum Supply Annual 1991*, 1992) (Tables 32 and 33). On the basis of this comparison, we assumed that relative to refineries nationally, California refineries:

- consumed 5% more total process energy per unit of output than did national refineries, for all products;
- consumed less residual fuel oil, petroleum coke, and natural gas, but more LPG, refinery gas, marketable coke, and steam;
- received much more crude oil by tanker, and less by pipeline.

We also assumed that California refineries emit less VOCs and NO_X, per unit of product, than do refineries nationally.

4.6.2 Converting emissions of non-CO_2 greenhouse-gases to an equivalent amount of CO_2

In order to estimate the combined effect on climate of emissions of all of the different greenhouse gases, mass emissions of the non-CO_2 greenhouse gases -- CH_4, CO, N_2O, NMHCs, and NO_x -- are converted into the mass amount of CO_2 emissions that would cause the same degree-years of warming over a given period of time. The conversion factor has been dubbed a “global warming potential”, or GWP.

To calculate a GWP, one needs to know, for both CO_2 and non-CO_2 gases, the relationship between equilibrium surface temperature and equilibrium atmospheric concentration, and the relationship between an increase in yearly emissions and the increase in the equilibrium atmospheric concentration. One also must consider interactions between gases (for example, CO and CH_4), and the ultimate fate of the gases (CH_4 ends up being oxidized to CO_2 and H_2O by the OH^- radical). Finally, one must pick a period of time to do the analysis: because one is equating "degree-years" of warming over a period of time, the equation will depend on the length of time chosen. This choice is important.

The GWPs used in this analysis (nominally for a 100-year time horizon) are shown in Table 34, and are discussed in more detail in Delucchi (1995d). It is important to keep in mind that the GWPs, while quite useful, also are very uncertain, and may be revised in the future, perhaps substantially (Intergovernmental Panel on Climate Change, 1992).

4.7. Emissions from the construction of vehicles, facilities, and guideways

For two reasons, we do not estimate emissions from the construction of vehicles, facilities, or guideways. First, because the timing and location of emissions matters a great deal, one should not add or compare construction emissions, which occur over a relatively short period of time at the beginning of a project, to emissions from system operation, which occur after construction emissions and can continue for decades. Certainly, it is not meaningful to annualize construction emissions and add them to emissions from operation, because neither pollution nor its effects act this way[12].

Second, the energy-use and emission-factor data needed for the estimation are poor. There is much disagreement about the energy requirements of guideway construction (Congressional Budget Office, 1977), and the emission factors for off-road construction equipment are not reliable (EPA, 1994).

5.0 ACCESS TO AND CIRCUITY OF TRIPS INVOLVING TRANSIT

5.1 Modes of access to line-haul transit

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[12] Of course, by this argument, one really should not simply add emissions from different sources in a fuelcycle (e.g., petroleum refineries and vehicles), or compare emissions from one fuelcycle (e.g. gasoline) with another (e.g., methanol). Technically, this is correct. However, we feel that the timing and locational differences between emissions sources and fuelcycles are minor compared to the differences between construction emissions and operational emissions.

The total emissions of a trip that uses bus or rail transit for the line haul depend greatly on whether the traveler walks, drives, or takes a bus or train from her home to the main bus stop or rail station. We analyzed data from the *1991 Statewide Travel Survey* of California (Caltrans, 1993) in order to quantify how travelers accessed public transit, on average, in the San Francisco, Sacramento, Los Angeles, and San Diego regions.

Tables 35 to 39 show the results of the analysis. For each of six types of line-haul transit trips in the survey -- local bus, intercity bus, school bus, light rail, heavy rail (BART in the San Francisco area), and commuter rail (Caltrain in the San Francisco Area)[13] -- we show the fraction of trips accessed by each of 12 modes: walk, drive alone, car passenger, bicycle, local bus, intercity bus, school bus, light rail, heavy rail, commuter rail, dial-a-ride, and other mode. In order to match correctly modes of access to line-haul trips, we had to match trip starting and end times, for every person that reported taking transit. This reconstruction from original data of every transit trip recorded in the survey was very time consuming, but was the only way to quantify the distribution of modes of access to transit trips.

The analysis indicates that a surprisingly large fraction (65% to 85%) of bus and train passengers walked to the main bus or rail line, and that a relatively small fraction (10% to 20%) took a car. More people drove to train stations than to bus stops, and more people drove to BART than to any other mode, although the distribution of modes of access to light-rail stations was similar to that for BART. (We had expected that more people would have driven to BART). We caution, however, that there were so few transit users in the sample that the results might not be generalizable to the whole population. On-board surveys conducted in the 1970s and 1980s (and one conducted in Los Angeles in 1994) uniformly reveal that a greater percentage of transit users took a car to the stop or station than in our analysis (Table 40). Perhaps our results are skewed because of the relatively small sample. In scenario analyses (section 6), we test a scenario in which all HRT passengers drive to the train station.

5.2 Circuity of trips involving transit

A trip made by transit will not be exactly the same length as the same trip made by automobile. The greater the difference in trip length, of course, the greater the difference in emissions.

It generally is assumed that trips involving transit are longer, or more circuitous, then trips by automobile. Table 41 summarizes estimates of the relative circuity of transit trips, and the portion of the total transit trip that is devoted to the mode of access, from the widely cited but somewhat outdated Congressional Budget Office (CBO) (1977) study of the energy use of urban transportation modes. We do not have much faith in these estimates, however. The CBO estimates appear to be educated guesses; no source is cited, and the CBO merely says automobiles “generally are the most direct form of urban passenger transportation” (p. 11). The CBO also cautions that

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[13] Intercity rail -- AMTRAK -- also was included in the survey, but was not used as a line-haul by any of the respondents in the four regions. It was used as an access mode by one person.

the estimates are “highly variable and poorly documented” (p. 10). Furthermore, the CBO’s estimates of circuity were strongly criticized by the New York Transit Authority and the American Public Transit Association in written testimony submitted to the Committee that sponsored the study. Finally, there is some evidence from the 1990 Nationwide Personal Transportation Survey (Vincent et al., 1994), that the circuity of carpools and vanpools is less than estimated by the CBO (Table 41).

5.3 Our assumptions

On the basis of the data in Tables 35 to 41, we estimated the length and modes of access to buses and trains (Tables 42 and 43).

5.4 A note on average auto occupancy and total person-trips by automobile.

Although we have not estimated “average” emissions per passenger mile of travel by auto (instead, we have analyzed different trip scenarios), it is possible to use our data and methods to do this, and to compare the result with the average emissions per passenger-mile of travel by transit. To estimate average emissions per passenger mile of travel, one must know either the “average” automobile occupancy, or else the total number of passenger-miles of travel by motor vehicles. These statistics often are reported in travel surveys, such as the Nationwide Personal Transportation Survey. However, as explained next, the average occupancy or total number of passenger miles, *as reported in travel surveys*, is not the correct measure to use.

As Vukich noted in testimony before the U.S. Senate (1977), the average automobile occupancy, and the total number of person-trips and passenger miles in motor vehicles, as determined by travel surveys, include trips by drivers who merely chauffeur someone else. These chauffeur trips actually should not be counted. Suppose, for example, that 10 fathers drive their kid to and from school each day, 2 miles one way. In travel surveys, this will be recorded as 120 person miles of travel. But if the parent does nothing other than chauffeur the child -- i.e., if the parent would not go out if the kid could get herself to school -- then the parent’s is not a purposeful motor-vehicle trip, and should not be counted in comparisons with transit. If the children were to take transit, the parent would not go along, and there would be only 40 person-miles of travel (assuming the same distance by transit as by car). Now, if the transit vehicle uses as much energy as do the 10 motor-vehicles, then a correct measure of energy use per passenger mile gives the same result for the transit system as for the motor-vehicle system. This correct result will be obtained only if the chauffeur’s person trips by car are not counted.

Thus, when comparing the “average” energy use or emissions or cost per passenger-mile of auto travel with the average for transit, trips by chauffeurs should not be counted.

6.0 RESULTS OF THE ANALYSIS

6.1 Summary of the base case

Table 45 shows the results of the “base-case” analysis. The percentage change in emissions is calculated as 100*(Tr-Ad)/Ad, where Tr is grams emitted per passenger trip involving transit, and Ad is grams emitted per direct door-to-door auto trip. A negative percentage change means that transit reduces emissions per passenger trip. The results of Table 45 include missions from fuel production and station and infrastructure operation and maintenance are included. For transit, emissions from access trips are included.

The base case uses the parameter values presented throughout this report (e.g., Tables 1, 3, 42, 43, 44). The base-case is just a scenario, not a prediction of fuels, modes, vehicle occupancy and other factors in particular regions. In the following sections we examine many other scenarios.

The base case uses CARB’s EMFAC emission factors for the year 2003 (e.g., Tables 11 and 14). These emission factors incorporate CARB’s assumptions about fuel quality and emission standards in the year 2003. The alternative fuel vehicles are assumed to be advanced-technology vehicles optimized to run on one fuel.

For the purpose of establishing an interesting base case, we have assumed that different regions will use different fuels and vehicle types. Our base-case assumptions about types of fuels (e.g., gasoline or electric vehicle) and types of cars (i.e., passenger car or van) are shown in Table 44. For example, we model EVs in the base-case for San Francisco. This, however, is just a scenario, not a prediction that EVs necessarily will be widely used in San Francisco.

The first and most important thing to notice about the percentage changes of Table 45 is that they vary considerably: transit uses causes increases in emissions of pollutants in some places and decreases in others, compared to direct automobile trips. For example, the use of LRT in Sacramento results in a considerable decrease in emissions of all pollutants except SO_X, whereas the use of HRT in Washington has a mixed effect. This is because the LRT system in Sacramento is more energy efficient than the HRT system in Washington (Table 4), and the electricity generation mix has less coal (Tables 16 and 20).

Next, note that LRT in San Diego does not provide quite as much as emissions reduction as does LRT in Sacramento. This is due partly to LRT being matched against CNG vehicles in San Diego, and gasoline vehicles in Sacramento; CNG is cleaner than gasoline (Table 12).

Wherever the occupancy of the direct-drive vehicle is high -- the carpools in Los Angeles, Boston, and San Francisco -- emissions from transit trips (at average transit-vehicle occupancy) tend to be higher than emissions from the direct-drive automobile trip. In the scenario analyses, we will examine the impact of increasing the occupancy of transit vehicles.

Finally, note that because we could not find data on emissions of emissions of acetaldehyde, 1,3-butadiene, and ethylene from power plants (Table 22), the percentage changes shown in Table 45 overstate the benefit of using electric transportation options.

In the next section we summarize the important parameters in the model, and in the sections after that we examine the effects of varying the values of these important parameters.

6.2 The important parameters

The preceding analysis of the base case, as well as the mechanics of our model, indicate that several parameters are important in the comparison of emissions from transit trips with emissions from direct-drive automobile trips:

- energy consumption per vehicle mile
- vehicle occupancy
- type of fuel used by cars, vans, or buses
- mix of fuels used to generate electricity
- mode of access to transit
- road dust and "track dust" emissions

In the following scenario analyses, we investigate the effect on emissions of varying these important parameters.

6.3 Scenario analyses

6.3.1 Base case. The same as the base case discussed above.

6.3.2 Base case without alternative fuels. In this scenario, all buses run on diesel fuel, and all cars and vans run on gasoline. Everything else is the same as in the base case (scenario 1). These changes from scenario 1 tends to make transit look somewhat better -- i.e., to reduce increases in emissions due to transit, or increase reductions -- because gasoline and diesel fuel are dirtier than alternative fuels. Put conversely, switching from conventional fuels to alternative fuels tends to reduce the advantage of transit, unless the alternative fuels are used in access trips and by transit buses, in which case the changes can be mixed (e.g., Los Angeles in this scenario).

6.3.3 Gasoline LDVs; no carpools; LRT transit. This case compares direct single-passenger trips in gasoline autos with trips involving light-rail transit, in which any motor-vehicle access to LRT stations is by single-passenger gasoline automobile or diesel-fuel bus. Everywhere except Boston, the LRT transit trip produces much lower emissions of every pollutant except SO_X than does the direct single-passenger gasoline-auto trip , because everywhere few people drive to LRT stations, and everywhere but Boston LRT uses relatively little energy. The LRT system in Boston apparently uses quite a bit of electricity (Tables 4 and 7; but note qualifications to estimates therein), which is produced from relatively dirty sources such as fuel oil (Table 20).

6.3.4 Gasoline LDVs; no carpools; HRT transit. This is the same as scenario 3, except that the transit trip is by heavy rail instead of light rail. Generally, the results are similar to the results of scenario 3. If the LRT system in a particular place is more energy intensive than is the HRT system (see Table 4), then it tends to produce higher emissions than does the HRT system (e.g., San Francisco and Boston), and vice versa. Overall, the trips involving HRT tend produce fewer emissions than do the direct single-passenger gasoline-auto trips.

6.3.5 Gasoline LDVs; no carpools ;diesel buses. This is the same as scenarios 3 and 4, except that the transit trip is by diesel bus instead of by rail. However, there are significant differences between the results of this scenario and the results of the rail scenarios. Buses emit more NMHC, CO, and NO_X than do power plants, and hence these emissions are higher (compared to single-passenger auto emissions) in this scenario than in the previous rail scenarios. In fact, NO_X emissions from the bus trip here are higher than NO_X emissions from the single-passenger gasoline auto trip. On the other hand, SO_X percentage changes decrease in this scenario compared to in the previous rail cases, on account of the use of low-sulfur diesel fuel by buses. PM_{10} emissions increase compared to the previous two rail cases, but because of road-dust emissions from buses, not tailpipe PM_{10} emissions. Still, PM_{10} emissions from buses are below PM_{10} emissions from the single-passenger gasoline auto trip.

6.3.6 Gasoline LDVs; no carpools; CNG buses. This is the same as scenario 5, except that all of the buses now use CNG instead of low-sulfur diesel fuel. This results in modest decreases in bus emissions across the board, compared to the previous diesel-fuel bus scenario, because CNG is somewhat cleaner than diesel fuel in every respect (Table 12).

6.3.7 Gasoline LDVs; EV vanpool to CNG buses. This is the same as scenario 6 except that in this scenario passengers who drive to the buses drive in an electric vanpool instead of a single-passenger gasoline auto. This results in trivial reductions in transit-trip emissions of almost all pollutants in all places, compared to the previous gasoline-auto-access scenario. The reductions are trivial because, even though the electric van has far lower emissions per passenger mile than does single-person gasoline auto (on account of both the lower per mile-vehicular emissions of the EV, and the higher occupancy of the van), on average very few people drive to buses (Table 43) , so that in the aggregate it hardly matters what they drive or how many are in the vehicle.

6.3.8 Gasoline LDVs; EV vanpool to LRT. This is the same as scenario 7, except that the transit trip is by LRT instead of by bus. This also is the same as scenario 3, except that those who drive to the LRT here drive in an electric vanpool instead of a single-passenger gasoline auto. The use of the electric vanpool results in minor reductions in LRT emissions compared to scenario 3. The reductions are minor because few people drive to LRT stops anyway (Table 43). However, the fraction who drive to LRT is greater than the fraction who drive to buses (Table 43), so that the reduction in transit-trip emissions caused by using EV vanpools in place of single-passenger gasoline autos is greater with LRT than with buses. The LRT scenario here remains somewhat cleaner than the bus system of the previous scenario.

Note that these last two scenarios are favorable to transit, and hence result in large reductions in emissions compared to driving directly by automobile.

6.3.9 Gasoline LDVs; EV vanpool to CNG buses; high-occupancy buses (best for buses). This is the same as scenario 7, except that the occupancy has been increased to 90% (cf. base case of Table 4). This of course substantially reduces emissions per passenger trip: bus transit emissions in this scenario are uniformly lower than bus transit emissions in scenario 7 (at the base-case load factor). Moreover, in this scenario, the per-passenger trip emissions from bus transit are everywhere lower than per-passenger-trip emissions from the direct single-passenger auto; in most cases, the reduction is over 80%. This case, which is the "best for buses" (because of the access by EV vanpool, as well as the high occupancy) demonstrates the obvious importance of the load factor for transit.

6.3.10 Gasoline LDVs; EV vanpool to LRT; high-occupancy LRT (best for LRT). This is the best case for LRT, similar to the best case for buses (scenario 9). Any access trips by car are in an EV vanpool; any access trips by bus are in a CNG bus. The load factors are 90% (cf. base-case factors of Table 4), and furthermore, "track-dust" emissions, the rail analog of road-dust emissions, are assumed to be zero (see section 4.1.9). Everywhere, emissions of every pollutant per passenger trip are near zero, except for SO_X emissions in Boston and Washington, D. C., because of the large amount of oil and coal in the fuel mixes there (Table 20).

6.3.11 Gasoline LDVs; EV vanpool to HRT; high-occupancy HRT (best for HRT). Analogous to scenario 10.

6.3.12 Gasoline vanpools; gasoline LDVs to diesel buses (worst for buses). This is the same as scenario 5, except that the direct-drive trip by gasoline automobile is a vanpool instead of a single-passenger car. This scenario in effect tests the results of increasing the occupancy of the direct-drive automobile trips rather than of the bus-transit trips. As expected, the effect is considerable. Bus transit now causes a substantial increase in emissions of every pollutant (except for ethene, which buses apparently do not emit [Table 13]), everywhere, whereas in scenario 5, in which the buses were matched against the single-passenger auto, bus transit reduced emissions of many pollutants.

6.3.13 Gasoline vanpools; gasoline LDVs to HRT. This is the same as scenario 4, except that the direct-drive trip by gasoline automobile is a vanpool instead of a single-passenger car. This scenario in effect tests the results of increasing the occupancy of the direct-drive automobile trips rather than of the heavy-rail transit trips. It is interesting to note that the effect in this scenario is not quite as dramatic as the effect in the case of bus transit (scenario 12 vs. scenario 5). For example, comparing HRT to vanpools rather than to single-passenger cars (this scenario vs. scenario 4) we find only a moderate effect on relative emissions of NMHCs and CO. This is because the HRT line-haul produces much less emissions of NMHCs, CO, and toxics than do cars or vans at any occupancy, because power plants produce essentially zero NMHCs, CO, and toxics. The only NMHCs and CO emissions from the HRT system come from the automobiles used to access the trains. Hence, total NMHC and CO emissions from HRT trips are so low that the occupancy of the direct-drive gasoline vehicle does not have a dramatic effect on the percentage change in emissions. In this scenario there also is little change in PM_{10} emissions over scenario 4, because trains (we assume) produce much less "track dust" than cars do "road dust". On the other hand, in this scenario, HRT increases emissions of NO_X and GHGs, whereas in scenario 4 it decreased them, compared to the direct-drive gasoline vehicle trip. This is because power plants do emit lots of NO_X and GHGs, so that the occupancy of the competing mode (vanpool or single-passenger auto) does affect the percentage change in emissions per transit passenger trip.

6.3.14 EV vanpools; EV LDVs to HRT (worst for HRT). Scenario 13, though, still is not the worst for HRT. In this scenario, which is the worst, the competing direct-drive trip not only is a vanpool, but an electric vanpool. This is significant because now the inherent advantage of electric trains over gasoline autos -- near-zero emissions of NMHCs, CO, and toxics from power plants -- vanishes, because the direct-drive autos (the electric vanpools) now use electric power too. The result now is that HRT causes a substantial increase in emissions of every pollutant except PM_{10}. (PM_{10} does not increase because the dominant source is road-dust, which we assume greatly exceeds "track dust" emissions.)

6.3.15 EVs; EVs to HRT. This is the same as scenario 14, except that the direct-drive trip by automobile is a single-passenger EV, rather than a EV vanpool. Reducing the occupancy of the direct-drive auto trip back to one (compared to several in scenario 14) cuts the emissions increases caused by HRT, and in the case of NO_X and SO_X actually reverses them, to decreases relative to direct-drive by automobile. This scenario demonstrates again that the occupancy of the direct-drive automobile has a more noticeable effect on the comparison between auto and transit when the automobile and the transit use the same motive technology (either electric power or internal combustion for both).

6.3.16 Gasoline vanpools; high-occupancy buses. This is similar to scenario 5, except now both the buses and the direct-drive autos have high occupancy: the buses are 90% full, and the direct-drive automobile is a vanpool. Qualitatively, the emissions results of this scenario are similar to those of scenario 5, which means that the effects of the increased occupancies roughly cancel. The result of increasing the occupancy of both buses and door-to-door automobiles is that buses are slightly worse in Washington D. C., Los

Angeles, and San Francisco, slightly better in Sacramento and Boston, and roughly the same in San Diego. The changes in relative emissions, however, are minor. Overall, one may conclude that one does just as well to increase automobile occupancy as to increase bus occupancy.

6.3.17 Gasoline cars; HRT with all access by gasoline auto. This is the same as scenario 4, except that everyone drives a single-passenger gasoline car to the train station (cf. base-case assumptions in Table 43). This causes a slight to large increase in emissions from HRT trips relative to emissions from direct-drive single-passenger auto trips. However, HRT still results in substantial reductions of emissions of every pollutant except SO_X everywhere. Thus, the fraction of people who drive to a rail station can affect the magnitude of the emissions reduction provided by HRT, but cannot switch the sign and cause HRT to increase emissions.

6.4 Conclusions

We have made a detailed model of emissions from transportation modes, in order to test the effects of transit use on emissions of several pollutants, in a wide range of situations. Depending on the values of key parameters -- energy use, vehicle occupancy, fuel type, mode of access, etc. -- the effect of transit use can range from a near elimination of all emissions per passenger trip to a substantial increase in all emissions per passenger trips.

It should come as no surprise that we cannot make sweeping generalizations about the effect of transit on air quality. (The most sweeping statement that we will venture is that rail transit generally will provide a substantial decrease in emissions of most pollutants.) Because the key parameters can assume vastly different values from one place or policy to another, the effect of transit must be analyzed case-by-case. The modeled developed here is a detailed enough to be a useful tool for case-by-case analysis.

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FIGURE 1. IDEALIZATION OF MODAL EMISSIONS FROM MOTOR VEHICLES OVER THE FEDERAL TEST PROCEDURE (FTP) (G/MI EMISSIONS VERSUS DISTANCE)

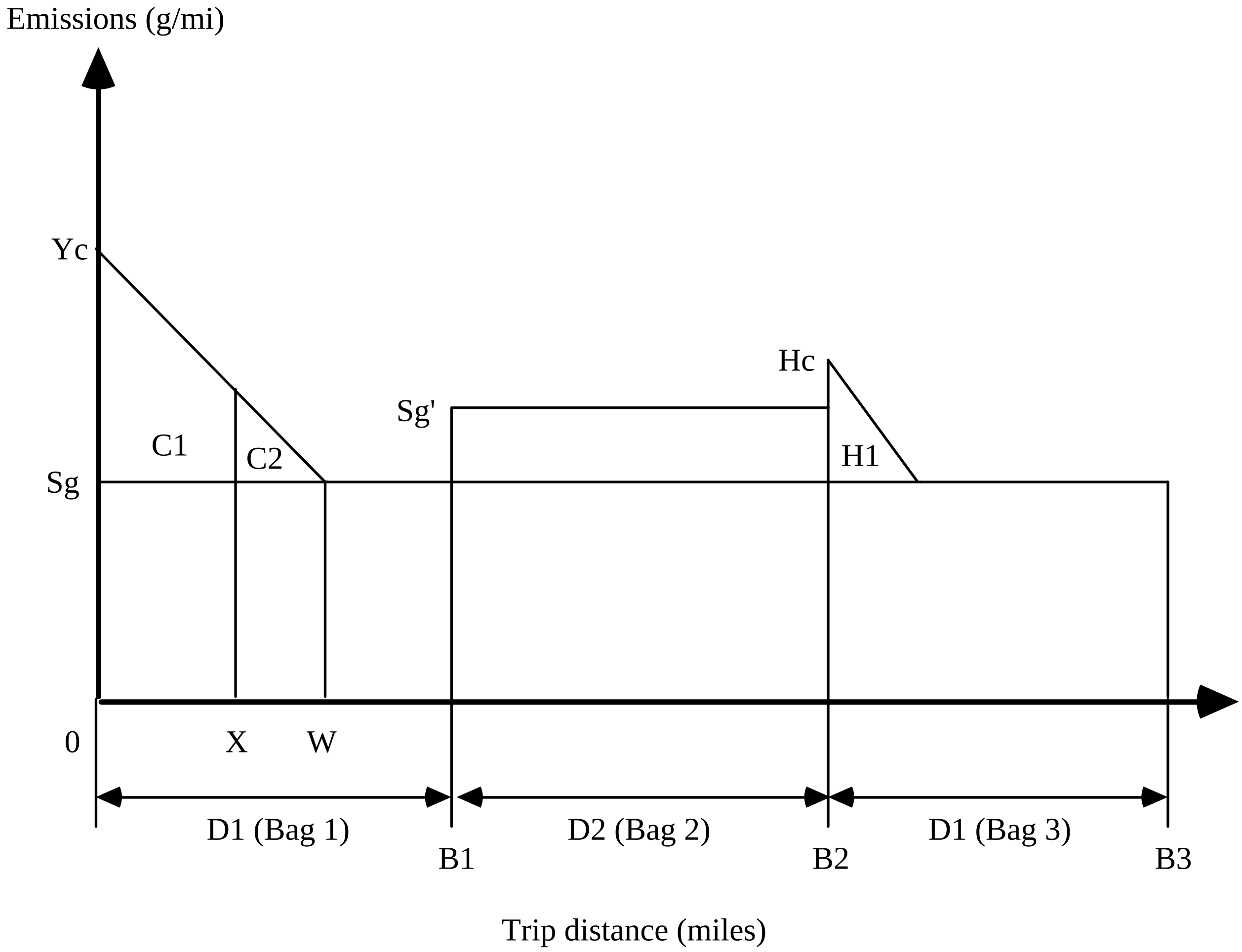

TABLE 1. FUEL USE BY LIGHT-DUTY CARS AND VANS: MODEL INPUT AND RESULTS FOR SACRAMENTO AND SAN FRANCISCO

	Sacramento		**San Francisco**	
Input vehicle parameters	*direct*	*access*	*direct*	*access*
Engine displacement (liters)	2.5	3.2	2.5	3.2
Thermal efficiency of gasoline engine (HHV, BTU / mi)[b]	0.37	0.37	0.37	0.37
Efficiency of the drivetrain	0.87	0.87	0.87	0.87
Efficiency of electrical system (for accessories)	0.5	0.5	0.5	0.5
Coefficient of drag	0.28	0.33	0.28	0.33
Frontal area (ft^2)	20.0	25.0	20.0	25.0
Empty weight of gasoline vehicle (lbs)	2750.0	3950.0	2750.0	3950.0
Number of people in car[a]	1.0	1.0	2.4	4.8
Weight per person (lbs)	150.0	150.0	150.0	150.0
Cargo (lbs)	0.0	0.0	0.0	0.0
Coefficient of rolling resistance	0.010	0.010	0.010	0.010
Accessory power, without air conditioning	0.50	0.60	0.50	0.60
Fraction of trip time that a / c is at full power	0.30	0.30	0.30	0.30
Revolutions per hour / mph (revolutions / mile)[b]	2508.0	2508.0	2508.0	2508.0
ICEV engine speed during idling (rpm)	750.0	700.0	750.0	700.0
Average speed in gear * relative gear ratio (mph)[b]	55.0	55.0	55.0	55.0
Engine energy consumption (kJ / revolution / liter, HHV)[b]	0.22	0.22	0.22	0.22
Correction factor for cold starts (kJ / revolution, HHV)[b]	1.10	1.10	1.10	1.10
Input trip parameters				
Length of trip, one way (miles)[d]	12.0	2.4	11.8	3.1
Fraction of trips that start with hot start	0.10	0.20	0.20	0.36
Fraction of trips that start with cold start	0.90	0.80	0.80	0.64
Average speed while moving (mph)[d]	40.77	33.98	28.28	22.54
Maximum speed (mph)	60.0	45.0	60.0	45.0
Number of stops per mile[e]	1.1	2.5	1.2	3.7
Fraction of trip time spent stopped[f]	0.190	0.209	0.209	0.240
Fraction of trip time that vehicle is coasting[f]	0.295	0.325	0.325	0.373
Fraction of trip time that engine is loaded[g]	0.705	0.675	0.675	0.627
Driving-cycle braking correction factor[b]	0.9	0.9	0.9	0.9

Calculated parameters				
Extra weight of AFV, divided by weight of empty baseline gasoline vehicle[h]	0.000	0.015	0.200	0.200
Thermal efficiency of selected vehicle relative to gasoline[h]	1.00	1.10	1.50	1.50
Total vehicle weight, including passengers (lbs)	2,900	4,160	3,661	5,463
Engine thermal efficiency (HHV)	0.370	0.407	0.555	0.555
Energy-use constant (kJ/revolution, HHV)[i]	0.605	0.704	0.000	0.000
Air-resistance coefficient (dimensionless)	0.0010	0.0013	0.0006	0.0009
Tire-resistance coefficient (dimensionless)	0.400	0.522	0.337	0.503
Braking coefficient (dimensionless)	1.839	2.398	0.928	1.385
Full power of air conditioning (kW)	3.17	3.78	3.17	3.78
Power for accessories and a/c (average kW over trip)	5.28	5.74	3.52	4.21
Average engine speed while vehicle is moving (rps)	30.7	29.7	29.9	28.4
Average vehicle speed over whole trip (mph)	33.0	26.9	22.4	17.1
Total time for trip (minutes)	21.8	5.4	31.7	10.8
Fuel consumption (kJ/meter, HHV)	3.25	4.42	1.41	2.54
Miles per million BTU (HHV)	202	148	464	258
Miles per gallon (mpg gasoline equivalent, for AFVs)	*24.6*	*18.1*	*56.7*	*31.5*

Source: our adaptation and specification of the model described in Ross (1994), An and Ross (1993), and Ross and An (1993). HHV = higher heating value; BTU = British Thermal Unit; AFV = alternative-fuel vehicle; a/c = air conditioning; ICEV = internal combustion engine vehicle. We assume that: i) a car used to access transit stations is smaller than a car used in the baseline door-to-door (direct) trip; but ii) a van used to access transit stations is the same as a van used in the baseline door-to-door (direct) trip, but carries fewer people. The “direct” columns labeled “direct” pertain to the vehicles that go door to door directly, from origin to destination. The columns labeled “access” pertain to the vehicles that go from home to a bus or train station.

The characteristics of the vehicles, and their calculated performance and emissions, depend of course on the type of fuel used (e.g., gasoline or CNG or electricity), and whether the vehicle is a van or passenger car or a carpool or vanpool. For the purpose of establishing an interesting base case, we have assumed that different regions will use different fuels and vehicle types. Our base-case assumptions about types of fuels (e.g., gasoline or electric vehicle) and types of cars (i.e., passenger car or van, or vanpool or carpool) are shown in Table 44. Note that these assumptions are just a base-case scenario, not predictions of which types of vehicles and fuels will be used in particular regions. For example, we model EVs in the base-case for San Francisco, but this is just a scenario, not a prediction that EVs necessarily will be widely used in San Francisco. (Note that in this table the EVs weigh more but also are more efficient than the gasoline ICEVs.) We actually run the model for a variety of scenarios.

[a] Rossetti and Eversole (1993) report the number of commute trips by 2-person vehicle pools, 3-person vehicle pools, and 4-plus-person vehicle pools in 25 major metropolitan areas in 1990. We assume that 4-plus-person pools carried 5 people on average, and then calculate the average occupancy in all vehicle pools (car pools and van pools) for the journey-to-work trip in Sacramento, San Francisco, Los Angeles, San Diego, Boston, and Washington, D. C. in 1990. Then, we assume that the average occupancy in carpools (whether for access trips or baseline direct trips) is equal to this calculated average, and that vanpools carry 2.5 times as many people as the average car pool for the baseline door-to-door trip, and 2.0 times as many for the access-to-transit trip.

[b] The values of these parameters are from Ross, An and Ross (1993) and Ross and An (1993). The values of the other parameters either our are assumptions or else are taken from a variety of standard data sources for motor vehicles. The parameter “Average speed in gear * relative gear ratio” is the speed (mph) of the vehicle, when in the highest gear, at which the engine speed is the same as it is in all other gears (Ross, 1994). It is simplified representation of a relationship between gear ratios and vehicle speed, and is used to calculate the number of engine revolutions, which in turn is multiplied by the energy consumption per revolution per liter, to estimate the total energy required to overcome engine friction.

[c] This is assumed to be zero for EVs.

[d] The average speed while moving is equal to the average overall speed over the whole trip divided by the fraction of time that the vehicle is moving. We use data on commute time and commute length by city, from the 1990 U.S. Census, the 1990 Nationwide Personal Transportation Study, and other sources (Rossetti and Eversole, 1993; Vincent et al., 1994; Gordon and Richardson, 1994) to estimate the length and average overall speed of the baseline (direct) trip by single-passenger vehicle. (We assume that for most trips, vehicles move about 80% of the time, and are stopped 20%.) Then, we use data on modes of access to transit and trip circuity (e.g., Tables 40 and 41) and some additional assumptions to estimate the length of transit-access trips and of carpool and vanpool trips, relative to the length of the baseline direct single-passenger vehicle trip.

[e] These our are assumptions and estimates. We assume that transit-access trips involve more stops per mile than do baseline direct trips, and that there is one stop to pick up each passenger in a van pool or car pool.

[f] For baseline direct trips by single-passenger autos or vans, we use An and Ross’ (1993) and Ross and An’s (1993) Federal-Test-Procedure values. We assume that the value increases with increased stop-and-go driving, so that it is higher for transit-access trips than for direct baseline trips, and higher for vanpools and carpools than for single-passenger autos.

[g] Equal to 1 minus the fraction of time coasting.

[h] These factors are used if an alternative-fuel vehicle, with a weight and thermal efficiency different from that of the gasoline vehicle, is specified.

[i] This is used to estimate the total frictional resistance (mechanical losses) and idling energy of an internal combustion engine, and therefore is assumed to be zero for an electric vehicle. Energy losses in the electric drivetrain are accounted for entirely in the efficiency term “Thermal efficiency of selected vehicle relative to gasoline” (see note g).

TABLE 2. FUEL, EMISSIONS, AND VEHICLE PARAMETERS FOR ALTERNATIVE-FUEL VEHICLES (BASE-CASE ASSUMPTIONS)

	Petrol.	**MeOH**	**CNG**	**LPG**	**EtOH**	**EVs**
Light-duty alternative-fuel vehicles						
Engine efficiency relative to petrol. (mi / BTU, HHV)	1.00	1.15	1.1	1.1	1.14	1.50[a]
Extra weight of AFV / weight of petroleum ICEV	0.00	0.00	0.045	0.015	0.00	0.200
Fraction of acceleration energy recovered by regenerative braking	0.00	0.00	0.00	0.00	0.00	0.40
Heavy-duty alternative-fuel vehicles						
Engine efficiency relative to petrol. (mi / BTU, HHV)	1.00	0.95	0.85	0.85	0.93	n.a.
Extra weight of AFV / weight of petroleum ICEV	0	0	0.035	0.002	0	n.a.
All alternative-fuel vehicles						
g-C / million BTU fuel	18,708	17,419	14,624	17,180	18,426	0.0
Carbon fraction in NMHC emissions	0.83	0.4	0.82	0.82	0.55	n.a.
Emissions from normal incidental burning of lubricating oil in the engine (g / mi)	2.0	2.0	1.0	1.5	2.0	0.0
Upstream GHG emissions (g / 10^6 BTU)[b]	22,808	42,662	14,550	9,992	94,419	

Notes: see next page.

Source of all estimates except “fraction of energy from biomass”: DeLuchi (1991, 1993). Assumptions pertain to advanced AFVs optimized to run on a single fuel. Petrol. = petroleum (reformulated gasoline or low-sulfur diesel fuel); MeOH = methanol; EtOH = ethanol; CNG = compressed natural gas; LPG = liquefied petroleum gases; AFV = alternative-fuel vehicle; ICEV = internal-combustion engine vehicle; BTU = British Thermal Unit; C = carbon; HHV = higher heating value; NMHC = nonmethane hydrocarbons; GHG = greenhouse-gas n.a. = not applicable.

[a] This is the once-through efficiency of the electric charger, battery, controller, motor, and transaxle, relative to that of the gasoline-vehicle engine and transmission.

[b] These are CO_2-equivalent emissions of all greenhouse gases, from the entire fuel-production and use cycle. For each end-use fuel (petroleum, methanol, etc.), the g / 10^6-BTU fuelcycle emission factor shown here is equal to the g / 10^6-BTU factor for each feedstock (coal, natural gas, wood, or corn) that the fuel can be made from (Table 31), multiplied by the following assumed base-case feedstock fractions:

	End use fuel		
	Methanol	*Ethanol*	*CNG*
natural gas feedstock	0.75	0.0	0.95
coal feedstock	0.1	0.0	0.0
corn feedstock	n.a.	0.8	0.0
wood feedstock	0.15	0.2	0.05

These fractions are just assumptions, made to have an interesting base-case scenario.

TABLE 3. FUEL USE BY DIESEL BUSES

	Sacra-mento	**San Francisco**	**Los Angeles**	**San Diego**	**Boston**	**Wash., D. C.**
mpg of empty diesel bus[a]	3.18	2.39	2.83	3.23	3.45	2.50
Weight of empty diesel bus (lbs)[b]	33,000	33,000	33,000	33,000	33,000	33,000
Passenger capacity[c]	71	74	67	76	65	67
Actual number of passengers[c]	9	16	19	14	9	14
Weight per person (lbs)[d]	150	150	150	150	150	150
% change in mpg / 1% change in weight[e]	-0.55	-0.55	-0.55	-0.55	-0.55	-0.55

[a] We back-calculated the empty-weight mpg from:

$$Fe = \frac{Fa}{\left(1 + \frac{Wp \times P \times Cw}{Wb}\right)}$$

where:

Fe = fuel economy of empty bus (mpg)
Fa = actual fuel economy of bus with average number of passengers in fiscal year 1990 (mpg; Table 4)
Wp = weight per passenger (this table)
P = actual average number of passengers in fiscal year 1990 (this table)
Cw = % change in fuel economy per 1% change in bus weight (this table)
Wb = weight of empty bus (this table)

We need to know the empty-weight mpg, even though we know the actual mpg at the average load (Table 4), so that we can estimate the mpg with any load other than the average. We rearrange the formula above to estimate the loaded-weight mpg (for any load) as a function of the empty weight mpg and the number of passengers. (Of course, if one inputs the empty-weight mpg and the average number of passengers, the rearranged formula returns the actual average mpg, as it should.)

[b] The weight of the 26 heavy-duty vehicles (apparently mostly buses) tested by Wang et al. (1993) ranged from 31,000 lbs to 35,000 lbs.

[c] Actual data for fiscal year 1990, as reported to the Federal Transit Administration (Table 4).

[d] Our estimate.

[e] From studies reviewed in DeLuchi (1991, 1993), and other sources.

TABLE 4. ENERGY USE BY TRANSIT SYSTEMS, FISCAL YEAR 1990.

Transit system	**Mode**[a]	**Diesel fuel** *10^3 gal*	**Gas-oline** *10^3 gal*	**Elec-tricity** *10^3 kWh*	**Vehicle revenue miles** *10^3*	**Vehicle revenue capacity mi** *10^3*	**Vehicle revenue hours** *10^3*	**Passenger miles** *10^3*	**Ave. speed** *mi/hr*	**Load** *fraction of capacity*	**Energy use**[b] *BTUs/pass-mile*	**Energy use**[c] *BTUs capacity-mile*
Los Angeles												
SCRTD	MB	31,598.8	0.0	0.0	86,591.6	5,701,190.7	6,953.6	1,612,752.0	12.5	0.283	2,717.6	768.7
SCRTD	DRP				6,912.7	62,214.7	470.1	9,004.9	14.7	0.145	n.e.	n.e.
SCRTD	MBP				3,035.7	176,069.8	211.3	46,979.0	14.4	0.267	n.e.	n.e.
San Francisco												
MUNI	CC	0.0	0.0	4,094.0	566.3	36,245.8	132.3	11,877.7	4.3	0.328	1,176.0	385.4
MUNI	DRP				1,435.7	16,566.3	138.9	2,529.7	10.3	0.153	n.e.	n.e.
MUNI	MB	5,568.2	0.0	0.0	12,809.2	943,761.5	1,374.7	202,728.4	9.3	0.215	3,809.6	818.3
MUNI	SC	0.0	0.0	43,338.1	4,092.8	556,626.0	385.4	109,484.4	10.6	0.197	1,350.6	265.7
MUNI	TB	0.0	0.0	35,121.0	7,355.5	551,665.9	988.7	119,787.2	7.4	0.217	1,000.4	217.2
BART	MBP				2,451.6	147,094.1	120.6	19,273.7	20.3	0.131	n.e.	n.e.
BART	RR	0.0	0.0	199,420.2	40,328.0	4,355,421.3	1,404.7	891,228.9	28.7	0.205	763.5	156.2
Golden Gate TD	FB	862.5	0.0	0.0	144.0	76,286.2	11.6	17,606.3	12.4	0.231	6,794.7	1,568.2
Golden Gate TD	MB	1,938.8	0.0	0.0	7,055.7	375,188.9	375.7	124,260.0	18.8	0.331	2,164.1	716.7
Golden Gate TD	MBP				434.3	19,532.0	15.8	12,199.3	27.5	0.625	n.e.	n.e.
Caltrans	FBP				97.5	38,988.4	7.7	4,109.4	12.7	0.105	n.e.	n.e.
Caltrans	CR	2,508.3	0.0	0.0	2,451.0	356,820.6	75.8	123,483.2	32.3	0.346	2,817.4	975.0
Sacramento												
Sacramento RTD	MB	2,135.1	2.2	0.0	6,596.6	471,194.8	480.4	61,462.3	13.7	0.130	4,822.7	629.1
Sacramento RTD	SC	0.0	0.0	7,200.0	1,373.0	240,273.4	72.1	30,783.1	19.0	0.128	798.0	102.2

San Diego												
San Diego TS	DRP				572.3	4,005.9	43.2	724.8	13.2	0.181	n.e.	n.e.
San Diego TS	MB	3,311.0	43.7	0.0	10,374.0	783,786.7	850.7	147,836.2	12.2	0.189	3,143.3	592.9
N San Diego Transit Dev	DR				549.8	6,992.9	34.6	682.0	15.9	0.098	n.e.	n.e.
N San Diego Transit Dev	MB	1,938.4	0.0	0.0	7,960.4	336,885.4	420.4	76,324.3	18.9	0.227	3,522.5	798.1
San Diego Region TS	DRP				2,457.6	16,690.8	156.4	4,614.7	15.7	0.276	n.e.	n.e.
San Diego Region TS	MBP				4,131.7	207,306.0	273.5	34,033.3	15.1	0.164	n.e.	n.e.
San Diego Trolley	SC	0.0	0.0	19,728.0	4,014.7	760,450.2	184.5	115,518.2	21.8	0.152	582.7	88.5
Washington, D. C.												
WMATA	MB	16,664.1	0.0	0.0	40,191.1	2,692,805.4	3,577.2	563,688.2	11.2	0.209	4,100.3	858.3
WMATA	RR	0.0	0.0	298,754.6	33,212.0	7,472,700.9	1,481.5	994,186.9	22.4	0.133	1,025.3	136.4
Boston												n.e.
MBTA	MBP				3,263.1	149,169.9	170.7	48,368.4	19.1	0.324	n.e.	n.e.
MBTA	DRP				1,793.8	n.r.	167.5	2,126.2	10.7		n.e.	n.e.
MBTA	FBP				121.3	59.8	9.1	6,475.0	13.3	108.278	n.e.	n.e.
MBTA	MB	6,703.9	0.0	0.0	22,644.7	1,471,904.7	1,876.8	198,621.3	12.1	0.135	4,681.4	631.7
MBTA	RR	0.0	0.0	143,853.1	23,186.3	3,451,282.2	1,098.9	546,476.9	21.1	0.158	898.2	142.2
MBTA	SC	0.0	0.0	36,146.1	1,295.0	226,549.9	116.9	32,696.7	11.1	0.144	3,772.0	544.4
MBTA	TB	0.0	0.0	3,389.9	745.3	48,447.7	57.4	6,871.3	13.0	0.142	1,683.3	238.7
Amtrak / MBTA	CR	7,487.0	0.0	0.0	13,186.1	1,577,210.4	505.6	348,394.4	26.1	0.221	2,980.7	658.4

Notes: see next page.

The data from the first nine columns, through “Passenger miles,” are from the UMTA / FTA section 15 data base. We calculated average speed, load, and energy use. n.e. = not estimated. n.r. = not reported.

[a] The modes are:
CC = cable car
CR = commuter rail
DR = demand ride
FB = ferry boat
MB = motor bus
RR = rapid rail
SC = street car
TB = trolley bus
“P” after any of the above indicates purchased transportation.

[b] Equal to diesel-fuel consumption multiplied by 138,700 BTUs / gallon plus gasoline consumption multiplied by 125,000 BTUs / gallon plus electricity consumption multiplied by 3412 BTUs / kWh, divided by passenger miles. (Thus, the energy use measure presented here does not account for energy losses in electricity generation.) This is propulsion energy only; it does not include energy for stations, buildings, or maintenance activities. However, propulsion or traction energy does include energy used for nonrevenue operation, as for our purposes it should.

[c] Equal to energy use per passenger mile multiplied by the load factor.

TABLE 5. ENERGY USE BY TRANSIT SYSTEMS, FISCAL YEAR 1989

Transit system	**Mode**[a]	**Diesel fuel** *10^3 gal*	**Gas-oline** *10^3 gal*	**Electricity** *10^3 kWh*	**Vehicle revenue miles** *10^3*	**Vehicle revenue capacity miles** *10^3*	**Vehicle revenue hours** *10^3*	**Passenger miles** *10^3*	**Ave. speed** *mi/hr*	**Load** *fraction of capacity*	**Energy use**[b] *BTUs/pass-mile*	**Energy use**[c] *BTUs/capacity-mile*
Los Angeles												
SCRTD	MB	27,979.6	0.0	0.0	86,149.7	5,851,000.0	6,861.5	1,648,700.0	12.6	0.282	2,353.8	663.3
Los Angeles County Transit	DRP				5,549.7	66,256.8	372.6	7,772.7	14.9	0.117	n.e.	n.e.
Los Angeles County Transit	FBP				0.0	0.0	0.0	0.0	n.e.	n.e.	n.e.	n.e.
Los Angeles County Transit	MBP				1,521.7	71,107.5	107.6	17,521.1	14.1	0.246	n.e.	n.e.
San Francisco												
MUNI	CC	0.0	0.0	3,826.2	554.7	35,502.2	130.3	11,861.2	4.3	0.334	1,100.6	367.7
MUNI	DRP				1,743.3	10,442.9	206.0	5,417.2	8.5	0.519	n.e.	n.e.
MUNI	MB	5,203.9	0.0	0.0	12,702.8	937,464.9	1,365.5	209,556.4	9.3	0.224	3,444.3	769.9
MUNI	SC	0.0	0.0	40,502.9	4,002.3	544,316.3	382.2	105,474.8	10.5	0.194	1,310.2	253.9
MUNI	TB	0.0	0.0	32,823.4	7,319.7	548,979.1	991.1	118,500.2	7.4	0.216	945.1	204.0
BART	MBP				1,170.7	70,244.8	55.8	n.r.	21.0	n.e.	n.e.	n.e.
BART	RR	0.0	0.0	172,259.6	33,195.1	3,817,436.4	1,158.1	757,350.0	28.7	0.198	776.1	154.0
Golden Gate TD	FB	779.6	0.0	0.0	138.1	72,467.3	10.8	15,702.9	12.8	0.217	6,886.0	1,492.1
Golden Gate TD	MB	1,838.3	0.0	0.0	6,825.9	374,757.7	360.7	116,642.7	18.9	0.311	2,185.9	680.4
Golden Gate TD	TMBP				423.9	19,024.5	15.5	12,457.9	27.3	0.655	n.e.	n.e.
Caltrans	CR	2,428.1	0.0	0.0	2,457.4	356,938.9	75.7	131,074.5	32.5	0.367	2,569.4	943.5
Sacramento												
Sacramento RTD	MB	1,729.8	38.2	0.0	5,863.6	418,898.1	420.9	57,786.3	13.9	0.138	4,234.5	584.1
Sacramento RTD	SC	0.0	0.0	6,899.2	1,059.8	184,458.7	53.6	21,633.7	19.8	0.117	1,088.1	127.6

San Diego												
San Diego TS	DRP				458.0	3,206.8	37.2	311.1	12.3	0.097	n.e.	n.e.
San Diego TS	MB	3,145.4	3.2	0.0	10,345.1	780,953.7	831.6	143,207.3	12.4	0.183	3,049.2	559.1
N San Diego Transit Dev	DRP				511.1	5,929.3	30.6	762.2	16.7	0.129	n.e.	n.e.
N San Diego Transit Dev	MB	1,877.1	0.0	0.0	7,828.0	335,819.3	403.9	69,960.7	19.4	0.208	3,721.4	775.3
San Diego Region TS	DRP				2,516.3	14,576.8	163.9	4,866.8	15.4	0.334	n.e.	n.e.
San Diego Region TS	MBP				3,334.2	146,215.8	206.7	28,254.1	16.1	0.193	n.e.	n.e.
San Diego Trolley	SC	0.0	0.0	11,297.7	2,366.5	507,682.5	125.5	75,936.6	18.9	0.150	507.6	75.9
Washington, D. C.												
WMATA	MB	16,432.5	0.0	0.0	39,350.2	2,636,460.3	2,860.7	530,498.7	13.8	0.201	4,296.3	864.5
WMATA	RR	0.0	0.0	295,240.9	32,859.0	7,393,277.3	1,405.5	978,315.0	23.4	0.132	1,029.7	136.3
Boston												
MBTA	MBP				799.8	n.r.	43.2	7,238.1	18.5	n.e.	n.e.	n.e.
MBTA	DRP				3,008.4	3,575.2	330.8	2,948.0	9.1	0.825	n.e.	n.e.
MBTA	FBP				110.0	n.r.	6.5	6,330.2	16.9	n.e.	n.e.	n.e.
MBTA	MB	7,183.8	0.0	0.0	23,239.7	1,505,896.1	1,958.8	232,547.7	11.9	0.154	4,284.7	661.7
MBTA	RR	0.0	0.0	148,853.1	21,857.5	n.r.	1,068.8	480,184.7	20.5	n.e.	1,057.7	0.0
MBTA	SC	0.0	0.0	49,542.9	1,183.8	131,277.8	79.2	28,754.5	14.9	0.219	5,878.7	1,287.7
MBTA	TB	0.0	0.0	1,389.9	742.1	48,201.1	57.0	8,454.2	13.0	0.175	560.9	98.4
Amtrak / MBTA	CR	7,473.1	0.0	0.0	13,211.3	1,519,305.1	429.3	330,133.9	30.8	0.217	3,139.7	682.2

Notes: see next page.

The data from the first nine columns, through “Passenger miles,” are from the UMTA / FTA section 15 data base. We calculated average speed, load, and energy use. n.e. = not estimated. n.r. = not reported.

[a] The modes are:
CC = cable car
CR = commuter rail
DR = demand response
FB = ferry boat
MB = motor bus
RR = rapid rail
SC = street car
TB = trolley bus
“P” after any of the above indicates purchased transportation.

[b] Equal to diesel-fuel consumption multiplied by 138,700 BTUs / gallon plus gasoline consumption multiplied by 125,000 BTUs / gallon plus electricity consumption multiplied by 3412 BTUs / kWh, divided by passenger miles. Thus, the energy use measure presented here does not account for energy losses in electricity generation. This is propulsion energy only; it does not include energy for stations, buildings, or maintenance activities. However, propulsion or traction energy does include energy used for nonrevenue operation, as for our purposes it should.

[c] Equal to energy use per passenger mile multiplied by the load factor.

TABLE 6. ENERGY USE BY TRANSIT SYSTEMS, FISCAL YEAR 1988

Transit system	**Mode**[a]	**Diesel fuel** *10^3 gal*	**Gas-oline** *10^3 gal*	**Electricity** *10^3 kWh*	**Vehicle revenue miles** *10^3*	**Vehicle revenue capacity miles** *10^3*	**Vehicle revenue hours** *10^3*	**Passenger miles** *10^3*	**Ave. speed** *mi/hr*	**Load** *fraction of capacity*	**Energy use**[b] *BTUs/pass-mile*	**Energy use**[c] *BTUs/capacity-mile*
Los Angeles												
SCRTD	MB	33,629.7	0.0	0.0	92,954.7	6,182,400.0	7,375.6	1,682,210.3	12.6	0.272	2,772.8	754.5
Los Angeles County Transit	DRP				2,389.7	17,222.5	152.1	4,635.4	15.7	0.269	n.e.	n.e.
Los Angeles County Transit	MBP				2,621.8	111,949.6	152.3	18,656.5	17.2	0.167	n.e.	n.e.
San Francisco												
MUNI	CC	0.0	0.0	3,831.0	544.9	34,872.6	128.3	13,405.0	4.2	0.384	975.1	374.8
MUNI	DRP				1,185.2	7,118.0	128.9	1,626.6	9.2	0.229	n.e.	n.e.
MUNI	MB	5,490.3	0.0	0.0	13,325.0	983,340.1	1,443.7	203,247.5	9.2	0.207	3,746.7	774.4
MUNI	SC	0.0	0.0	40,223.3	4,056.8	551,722.5	393.2	106,038.3	10.3	0.192	1,294.3	248.8
MUNI	TB	0.0	0.0	34,226.2	7,560.1	567,010.4	1,041.6	138,130.7	7.3	0.244	845.4	206.0
BART	RR	0.0	0.0	172,502.1	31,943.2	3,390,454.2	1,148.1	722,583.1	27.8	0.213	814.5	173.6
Golden Gate TD	FB	779.5	0.0	0.0	138.0	72,274.5	10.7	15,105.4	12.9	0.209	7,157.5	1,495.9
Golden Gate TD	MB	1,781.1	0.0	0.0	6,533.1	357,826.7	346.0	110,777.9	18.9	0.310	2,230.0	690.4
Golden Gate TD	MBP				422.1	20,263.1	15.5	12,431.5	27.2	0.614	n.e.	n.e.
Caltrans	CR	2,495.2	0.0	0.0	2,471.8	345,110.4	76.0	130,359.9	32.5	0.378	2,654.8	1,002.8
Sacramento												
Sacramento RTD	MB	1,907.5	45.3	0.0	5,917.8	420,167.1	423.5	56,319.1	14.0	0.134	4,798.2	643.2
Sacramento RTD	SC	0.0	0.0	8,644.5	936.2	163,832.2	47.0	20,381.7	19.9	0.124	1,447.1	180.0

San Diego												
San Diego TS	MB	3,143.4	34.8	0.0	10,782.7	668,921.7	816.9	125,497.7	13.2	0.188	3,508.7	658.3
San Diego TS	DRP				309.4	2,165.6	23.9	207.4	12.9	0.096	n.e.	n.e.
N San Diego Transit Dev	MB	1,780.7	0.0	0.0	7,651.4	522.6[d]	388.2	56,929.7	19.7	??	4,338.4	??
N San Diego Transit Dev	DRP				513.4	n.r.	32.4	881.9	15.8	n.e.	n.e.	n.e.
N San Diego Transit Dev	DRP				5,064.0	46,170.3	347.0	7,145.1	14.6	0.155	n.e.	n.e.
N San Diego Transit Dev	MBP				640.2	37,131.9	56.5	5,487.3	11.3	0.148	n.e.	n.e.
San Diego Region TS	DRP				3,119.6	14,661.6	341.1	3,497.6	9.1	0.239	n.e.	n.e.
San Diego Region TS	MBP				919.8	27,674.2	46.5	6,305.9	19.8	0.228	n.e.	n.e.
San Diego Trolley	SC	0.0	0.0	9,669.6						n.e.		n.e.
Washington, D. C.												
WMATA	MB	16,410.3	0.0	0.0	38,958.8	2,610,238.4	2,833.0	556,643.6	13.8	0.213	4,089.0	872.0
WMATA	RR	0.0	0.0	298,412.6	32,119.5	7,226,884.1	1,378.6	940,165.9	23.3	0.130	1,083.0	140.9
Boston												
MBTA	MB	7,910.7	0.0	0.0	23,387.3	1,515,140.3	1,972.8	239,310.0	11.9	0.158	4,584.9	724.2
MBTA	DRP				1,483.0	10,381.2	174.4	1,201.0	8.5	0.116	n.e.	n.e.
MBTA	FBP				71.9	6,333.0	4.0	5,224.5	18.0	0.825	n.e.	n.e.
MBTA	MBP				1,012.4	33,409.7	67.5	6,304.3	15.0	0.189	n.e.	n.e.
MBTA	RR	0.0	0.0	185,707.0	20,077.7	3,122,353.2	1,003.2	460,464.5	20.0	0.147	1,376.1	202.9
MBTA	SC	0.0	0.0	54,084.8	1,099.6	143,935.9	73.3	27,852.3	15.0	0.194	6,625.6	1,282.1
MBTA	TB	0.0	0.0	1,608.3	745.6	48,292.3	57.2	8,665.0	13.0	0.179	633.3	113.6
Caravan	VP				4,035.6	56,833.5	101.5	56,228.3	39.8	0.989	n.e.	n.e.

Notes: see next page.

The data from the first nine columns, through “Passenger miles,” are from the UMTA / FTA section 15 data base. We calculated average speed, load, and energy use. n.e. = not estimated. n.r. = not reported.

[a] The modes are:
CC = cable car
CR = commuter rail
DR = demand ride
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TB = trolley bus
“P” after any of the above indicates purchased transportation.

[b] Equal to diesel-fuel consumption multiplied by 138,700 BTUs / gallon plus gasoline consumption multiplied by 125,000 BTUs / gallon plus electricity consumption multiplied by 3412 BTUs / kWh, divided by passenger miles. Thus, the energy use measure presented here does not account for energy losses in electricity generation. This is propulsion energy only; it does not include energy for stations, buildings, or maintenance activities. However, propulsion or traction energy does include energy used for nonrevenue operation, as for our purposes it should.

[c] Equal to energy use per passenger mile multiplied by the load factor.

[d] This presumably is a typo, and should be 522,600. The original data are difficult to verify, and in any case, this particular datum is not used in this analysis.

TABLE 7. NON-TRACTION ENERGY USE BY SIX TRANSIT SYSTEMS

	Sacramento *Regional Transit*[a]	**San Francisco** *BART*[b]	**Los Angeles** *SCRTD*[c]	**San Diego** *Transit*[d]	**Boston** *MBTA*[e]	**Washington D. C.** *WMATA*[f]
Bus	*FY 1990*	*FY 1989*	*FY 1988*	*FY 1991*	*FY 1990*	*FY 1988*
electricity (kWh)	2,500,000	n.a.	48,000,000	3,482,893	12,610,000	19,682,466
diesel fuel (gallons)	2,647	n.a.	0	0	4,832	20,648
natural gas (SCF)	0	n.a.	75,811,013	9,422,087	0	0
gasoline (gallons)	28,041	n.a.	800,000	103,940	48,321	214,300
Light rail						
electricity (kWh)	900,000	n.a.	n.a.	n.a.	14,550,000	n.a.
diesel fuel (gallons)	953	n.a.	n.a.	n.a.	5,576	n.a.
natural gas (SCF)	0	n.a.	n.a.	n.a.	0	n.a.
gasoline (gallons)	10,095	n.a.	n.a.	n.a.	55,755	n.a.
Heavy rail						
electricity (kWh)	n.a.	60,879,743	n.a.	n.a.	69,840,000	177,142,197
diesel fuel (gallons)	n.a.	84,000	n.a.	n.a.	26,762	41,921
natural gas (SCF)	n.a.	40,550,118	n.a.	n.a.	0	0
gasoline (gallons)	n.a.	180,000	n.a.	n.a.	267,624	435,100
1000 passenger capacity miles[g]						
Bus	471,195	n.a.	6,182,400	801,658	1,471,905	2,610,238
Light rail	240,273	n.a.	n.a.	n.a.	274,998	n.a.
Heavy rail	n.a.	3,817,436	n.a.	n.a.	3,451,282	7,226,884

BTUs/passenger-capacity-mile						
Bus						
electricity[h]	55	n.a.	80	45	88	78
diesel fuel	0.8	n.a.	0.0	0.0	0.5	1.1
natural gas	0.0	n.a.	12.6	12.1	0.0	0.0
gasoline[i]	7.4	n.a.	16.2	16.2	4.1	10.3
Total for bus[j]	63	n.a.	109	73	93	89
Light rail						
electricity[h]	39	n.a	n.a.	n.a.	545	n.a
diesel fuel	0.6	n.a.	n.a.	n.a.	2.8	n.a.
natural gas	0.0	n.a.	n.a.	n.a.	0.0	n.a.
gasoline[i]	5.3	n.a.	n.a.	n.a.	25.3	n.a.
Total for light rail[j]	44	n.a.	n.a.	n.a.	573	n.a.
Heavy rail						
electricity[h]	n.a	164	n.a.	n.a.	208	252
diesel fuel	n.a.	3.1	n.a.	n.a.	1.1	0.8
natural gas	n.a.	11.0	n.a.	n.a.	0.0	0.0
gasoline[i]	n.a.	5.9	n.a.	n.a.	9.7	7.5
Total for heavy rail[j]	n.a.	184	n.a.	n.a.	219	261

Notes: see next page.

n.a. = not applicable (i.e., no bus or rail system); inc. below = included in the estimates below. BART = Bay Area Rapid Transit; SCRTD = Southern California Regional Transit District; MBTA = Metropolitan Boston Transit Authority; WMATA = Washington Metropolitan Area Transit Authority; FY = fiscal year; SCF = standard cubic foot. Passenger capacity miles are the same as revenue vehicle capacity miles (Tables 6 to 4).

[a] In fiscal year 1990, the Sacramento Regional Transit bus system used 2.5 million kWh of electricity, and the light-rail system used 0.9 million kWh of nontraction power (M. Lonergan, 1993). Non-revenue gasoline vehicles consumed 3178 gallons of gasoline in July 1990, and six nonrevenue diesel vehicles consumed a total of about 300 gallons per month (N. Fox, 1993).

[b] W. Belding (1993) provided the following data on the BART system:

	FY 1987	FY 1988	FY 1989
Million $, traction power	12.590000	10.703646	11.147025
Millions $, station & miscellaneous power	4.484551	4.004838	4.261582
Millions $, other utilities	0.813937	0.732208	0.836559

M. Epperson (1994) provided the following additional data:

	FY 1989	FY 1990
Millions kWh, station & miscellaneous power	65.336499	66.608617

Miscellaneous power includes power used by maintenance yards, shops, and the main administrative building. It does not include power used by leased buildings and some parking lots. To account for this other power, Epperson (1994) suggested multiplying by about 1.05 which we have.

Dividing FY 1989 expenditures on station and miscellaneous by FY 1989 power consumption indicates that BART spend $0.0653 / kWh for these uses. Dividing FY 1989 expenditures on traction power by FY 989 kWh for traction power (Table 5) indicates that BART paid $0.647 / kWh for traction power. This difference small difference, if real, is correct: BART gets a lower rate for traction power because the rail system takes power at the transmission-line voltage, without a voltage step-down (Epperson, 1994).

We assume that on quarter of BART's expenditures on utilities (other than electricity) were for natural gas, at $5.00 / 10^6BTU. (In SIC 75, automotive repair, expenditures on non-highway fuels actually exceed expenditures on utilities other than electricity [Bureau of the Census, *1987 Census of Service Industries, Capital expenditures, Depreciable assets, and Operating Expenses,* 1991], which suggests that at least half of BART's non-electricity utility bill could be for natural gas.) The EIA reports the following prices for natural gas in the Western U.S. in 1990 ($ / 10^6BTU, 1992$):

Region	*Residential*	*Commercial*	*Industrial*	*Transportation*	*All*
West South Central	5.78	4.41	2.78	3.32	2.96

From the EIA's *Supplement to the Annual Energy Outlook 1994* (1994).

Finally, BART vehicles consumed 15,000 gallons of gasoline and 7000 gallons of diesel fuel per month, over 6 months in 1988 and 1989 (M. Door, 1993).

[c] In FY 1988, Southern California Regional Transit District spent \$3.36 million for all power and \$0.0391 million for natural gas (F. Hadden, 1993). As explained in note b above, we assume \$5.00 / 10^6BTU for natural gas. On the basis of the following data, we assume \$0.07 / kWh for electricity:

Region	*Residential*	*Commercial*	*Industrial*	*Transportation*	*All*
California	0.089	0.086	0.067	0.051	0.080
New England	0.097	0.087	0.073	0.070	0.087

From the EIA's *Supplement to the Annual Energy Outlook 1994* (1994).

According to J Bowie (1993) of SCRTD, in most years SCRTD nonrevenue vehicles use 800,000 gallons gasoline and very little diesel fuel.

[d] The data shown are for FY 1991 (July 1990 to June 1991) (R. Perez, 1993). San Diego Transit paid \$5.83 / 10^6 BTU for gas and \$0.077 / kWh for electricity.

[e] The Metropolitan Boston Transit Authority consumed 101 million kWh and 82 million SCF of natural gas for nontraction purposes in FY 1990, excluding energy used for construction (N. Polcari, 1993; D. McCormick, 1995). Nonrevenue gasoline vehicles used 371,700 gallons of gasoline in FY 1991, and non-revenue diesel vehicles consumed "about 10%" of that amount (M. Dipaulo, 1993). We assigned 13% to bus, 6% to light rail (streetcar and trolley bus), and 81% to heavy rail (subway). (A small amount of the non-traction electricity actually powers AMTRAK stations; we ignore this here.) Traction energy: 76% of kWh usage is RT lines. Trolley and Street car is 23%. 1% to AMTRAK.

[f] WMATA (P. Reed, 1993) provided us with data on total consumption of gasoline, diesel fuel, and electricity for all stations, non-revenue vehicles, buildings, and maintenance facilities for the entire WMATA rail-and-bus system combined, in FY 1988. Then, they estimated that bus operations consumed 33% of the total gasoline and diesel fuel, and rail operations 67%. They also told us that "most" of the non-traction electricity use reported should be allocated to the rail system. We assumed 90%.

WMATA paid \$0.05 / kWh for electricity.

[g] From the Federal Transit Administration (1992).

[h] Electricity counted at 10,300 BTUs / kWh. Here this is just an accounting convention, applied to electricity to be able to add up all BTUs to get a bottom-line BTU total. In calculating emissions, however, we revert to the original kWh data; that is we calculate emissions due to electricity by multiplying actual kWh of electricity use per passenger mile by the marginal emissions rate per kWh delivered from the power plants in the particular region (e.g., Table 24).

[i] We assume conventional gasoline for these calculations.

[j] BTUs per passenger-capacity mile are divided by load factors (Table 4) to obtain BTUs / passenger mile, which of course are used to calculate the final results (Table 45).

TABLE 8. ESTIMATES IN THE LITERATURE OF STATION AND MAINTENANCE ENERGY USE BY TRANSIT SYSTEMS

System (reference)	**Fraction of total station + maintenance + vehicle**	
	vehicle operation	*Station and maintenance*
New heavy rail (subway and at grade)		
Bay Area Rapid Transit District (Fels, 1978)	0.71	0.29
Bay Area Rapid Transit District (Curry, 1976)[a]	0.66-0.76	0.24-0.34
Bay Area Rapid Transit District (this report)	0.55	0.45
Washington Metro (this report)	0.39	0.61
Los Angeles Metro Rail (Westec Services, 1983)[b]	0.54	0.46
Rapid transit below grade (Reno and Bixby, 1985)[c]	0.55-0.74	0.26-0.45
Rapid transit at grade (Reno and Bixby, 1985)[c]	0.79-0.91	0.09-0.21
Old heavy rail		
New York Subway (Fels, 1978)	0.86	0.14
PATH (New Jersey to New York) (Fels, 1978)	0.89	0.11
New commuter rail (at grade)		
PATCO Lindenwold line (Fels, 1978)	0.85	0.15
PATCO Lindenwold line (Curry, 1976)[a]	0.78	0.22
Light rail transit		
Light rail transit at grade (Reno and Bixby, 1985)[c]	0.67-0.85	0.15-0.33
Sacramento LRT (at grade) (this report)	0.86	0.14
Bus		
Sacramento Regional Transit (this report)	0.90	0.10
Southern California Regional Transit District (this report)	0.86	0.14
San Diego Transit (this report)	0.88	0.12
Washington Metropolitan Area Transit Administration (this report)	0.90	0.10

In general, there is some question as to the best way to add up electrical energy and energy from other sources, such as natural gas. However, for all of the systems included in this table, electricity is the main energy source for stations and maintenance as well as for vehicles, and in some cases, it is the only energy source. A relatively minor amount of natural gas, diesel fuel, and gasoline is used to heat buildings and fuel non-revenue vehicles. Because all or nearly all of the energy is electrical, the issue of converting to "common" BTUs is not important. Nevertheless, as far as we can tell, where necessary electricity has been converted at around 10,000 BTUs / kWh (the average heating rate of power plants) and added to the heat value of other fuels, which is a reasonable approach.

[a] Curry (1976) cites original energy impact analyses. Curry says that regenerative braking can return “up to” 20% of propulsion energy; we assume 0% to 10%.

[b] The station and maintenance energy requirements are relatively high because all of the stations are subway stations. By contrast, many BART and Washington-Metro stations are above ground. Subway stations consume more energy than above-ground stations because they use more lighting, elevators, and escalators.

[c] Reno and Bixby (1985) cite the 1982 book *Urban Rail in America*, by Pushkarev et al. In all cases, the range of values depends on the speed of vehicle operation; at higher speeds, the maintenance and station energy fraction declines.

We assume that the Pushkarev et al. estimates refer to new rail systems.

Calculated from the data of Tables 6 to 4 and Table 7, and data (not shown) from the FTA (1992). We have assumed 10,300 BTUs / kWh.

TABLE 9. CALCULATION OF ELECTRICITY AND FUEL USE IN SICS 517, 554, 55 (EXCEPT 554) AND 75, IN 1987

SIC: description	Electricity		Natural gas		Fuel oil	
	expense (10^6\$)[a]	*price (\$/kWh)*[c]	*expense (10^6\$)*[a,b]	*price (\$/SCF)*[d]	*expense (10^6\$)*[a,b]	*price (\$/gal)*[e]
517: Petroleum marketing	151	0.0600	84	0.00400	25	0.60
554: Service stations	666	0.0677	112	0.00563	33	0.71
55[f]: Motor vehicles, parts	750	0.0677	243	0.00563	73	0.71
751,754[g]: Leasing, services	165	0.0677	65	0.00563	19	0.71
752[g]: Parking	21	0.0677	5	0.00563	1	0.71
753[g]: Repair	281	0.0677	118	0.00563	35	0.71

[a] These data are from the Bureau of the Census' quinquennial surveys: data for SIC 517 are from the *1987 Census of Wholesale Trade, Subject Series, Measures of Value Produced, Capital Expenditures, Depreciable Assets and Operating Expenses* (1991); data for SICs 554 and 55 except 554 are from the *1987 Census of Retail Trade, Measures of Value Produced, Capital expenditures, Depreciable assets, and Operating Expenses* (1991); and data for SICs 751-754 are from the *1987 Census of Service Industries, Capital expenditures, Depreciable assets, and Operating Expenses* (1991).

The expenditure estimates published from these surveys are actual, direct payments for electricity and fuel; they do not include the cost of any electricity and fuel that was included in normal lease or rental payments or franchise fees. Therefore, the published expenditure estimates need to be scaled up to account for the use of electricity and fuel that was paid for in lease, rental, or franchise fees and hence did not show up in the published expenditures. Because the Census does not have any data on the cost of energy included in lease, rental, or franchise fees, this scaling must be done indirectly, as explained next.

The Census does have unpublished data that allow one to calculate the ratio of: total operating expenses for all firms in the SIC of interest (that is, operating expenses of firms that paid for electricity and fuel, *plus* the operating expenses of firms whose electricity and fuel use was covered by lease, rental, or franchise fees) to the operating expenses of firms that reported only direct payments for electricity and fuel (Bureau of the Census, Business Division, personal communication, 1993). We assume that this ratio is equal to the ratio that we would really like to know, namely: payments for all electricity and fuel (including the cost of electricity and fuel covered in lease, rental, or franchise fees) to reported actual payments for electricity and fuel. Therefore, we multiply reported direct payments for electricity and fuel in each SIC by the ratio of total operating expenses of all firms to operating expenses of firms that reported direct payments for electricity and fuel, in each SIC.

[b] The Census shows only total expenditures for all fuels other than electricity; it does not distinguish natural gas from fuel oil. We use data from the EIA's *Manufacturing Energy Consumption Survey* to estimate the portion of fuel expenditures that is for natural gas, and the portion that is for fuel oil. In 1986, mercantile and service commercial buildings in the U.S. consumed 0.536 quads and 10.58-billion-dollars-worth of electricity, 0.332 quads and 1.61

billion-dollars-worth of natural gas, 0.105 quads and 0.489 billion-dollars-worth of fuel oil, 0.012 quads of district heat, and 0.017 quads of propane (EIA, *Annual Energy Review 1993*, 1994). Based on this, we assume that in 1987, 23% of the payment for "other fuels" as reported by the Census was for fuel oil, and that 77% was for natural gas.

The Census also provided information on operating expenses that included use of "fuels not applicable." We have assumed that this refers to highway fuels, which we wish to include in our totals, so we have estimated payments for these fuels and have included them in the totals shown for fuel oil.

[c] In 1987, the average electricity price in the U.S. in the commercial sector as a whole was $0.0708 / kWh, and in 1986 the average electricity price to mercantile and service commercial buildings specifically was $0.0686 / kWh (EIA, *Annual Energy Review 1993*, 1994; the figure for 1986 is from the Commercial Buildings Energy Consumption Survey, which was done in 1986 and 1989 but not 1987). The price to mercantile and service buildings in 1987 can be approximated as the price in 1986 multiplied by the ratio of the price to the commercial sector as a whole in 1987 to the price to the commercial sector as a whole in 1986. This results in $0.0677 / kWh, which we use as the average electricity price in SICs 554, 55 except 554, and 75.

We assume that the price to SIC 517 is between the commercial-sector average price of $0.0708 / kWh and the industrial-sector average price of $0.0477 / kWh (EIA, *Annual Energy Review 1993,* 1994).

[d] We estimate the average natural gas using the same data source (EIA, *Annual Energy Review 1993*, 1994) and methods that we used to estimate the average electricity price (footnote c). The relevant price data for natural gas are: $4.77 / 1000-SCF (Standard Cubic Feet) to the commercial sector in 1987 and $5.08 in 1986; $5.29 / 1000-SCF to mercantile and service buildings in 1986; and $2.94 / 1000-SCF to the industrial sector in 1987.

[e] I estimate the average fuel-oil price using the same data source (EIA, *Annual Energy Review 1993*, 1994) and methods that I used to estimate the average electricity price (footnote c).The relevant price data for fuel oil are: $0.803 / gallon for residential heating oil in 1987, and $0.836 in 1986; $0.685 / gallon for "fuel oil" sold to mercantile and service buildings in 1986 (we assume 140,00 BTU / gallon HHV); and $0.527 / gallon for No. 2 fuel oil sold from refiners to resellers in 1987, and $0.486 / gallon in 1986.

[f] Excluding SIC 554, which is covered separately.

[g] The Census reported electricity and fuel expenditures in all of SIC 75, electricity and fuel expenditures in SIC 753, and electricity expenditures in SIC 754. We subtracted energy expenditures in SIC 753 from total energy expenditures in SIC 75, and apportioned the remaining energy expenditures among SICs 751, 752, and 754 according total operating expenditures (which were reported for all SICs).

TABLE 10. CALCULATION OF ENERGY USE FOR AUTO SERVICES, PER UNIT OF FUEL OR MILE OF TRAVEL

	Electricity (kWh)	**Natural gas** (SCF)	**Fuel oil** (gallons)
Energy use per 10^6 BTU of liquid fuel[a]			
Marketing (SIC 517)[b]	0.090	0.757	0.0015
Service stations (including repair) (SIC 554)[c]	0.812	1.636	0.0039
Energy use per 10^6 BTU of CNG			
Service stations excluding compression[d]	0.416	1.636	0.0039
Compression of natural gas[e]	6.450	0.0000	0.0000
Energy use per vehicle mile -- all vehicle types[f]			
Motor vehicle and parts sales; repair done at dealers and parts stores (based on SIC 55 except 554)[g]	0.0060	0.0232	0.00005
Auto services (based on SICs 751,754)[h]	0.0063	0.0300	0.0001
Commercial parking (based on SIC 752)[i]	0.0035	0.0095	0.0000
Auto repair n.e.c. (based on SIC 753)[j]	0.0024	0.0120	0.0000
Non-commercial parking (1990 data)[k]	0.0039	0.0000	0.0000

All values shown are equal to dollar expenditures on electricity or fuel divided by price (per kWh, SCF, or gallon) divided by total activity or quantity (BTUs or miles). Expenditure and price data are from Table 9. Activity data are documented in the notes to this table. SCF = standard cubic foot; SIC = standard industrial classification; CNG = compressed natural gas. Construction energy is not included anywhere in this table.

[a] We express energy consumption at petroleum storage plants and service stations per million BTU because that most accurately represents the real functional relationship: the more fuel stored or dispensed, the greater the energy usage at service stations and marketing facilities. Energy consumption at these facilities is not directly related to VMT because of the intervening effect of fuel economy (miles per 10^6 BTU). However, if you wish to know energy consumption per VMT, to compare with the energy consumption per VMT calculated for the other SICs, convert the result shown here to energy / gallon and then divide by 15.06 fleet-average mpg in 1987.

[b] We assume that electricity and fuel use at liquid-bulk-storage facilities is proportional to the amount of fuel handled. In 1987, SIC 517, petroleum bulk storage, sold 222.7 billion gallons of fuel (Bureau of the Census, *1987 Census of Wholesale Trade, Miscellaneous Subjects,* 1991). We

assume that all highway fuels pass through a bulk-storage facility, and that no gallon of any fuel is sold twice within SIC 517. We also assume that SIC 517 handles only petroleum products, and that there is no bulk storage of highway fuels outside of SIC 517. With these assumptions, the amount of energy used at bulk storage facilities per unit gallon of highway fuel consumed by end users -- which is the number that we want -- equals the total amount of energy (of each kind) consumed in SIC 517 divided by the total amount of gallons sold in SIC 517. The electricity and fuel-use and the gallon-sales data for SIC 517 are from the same general survey, but it appears that the definition of “petroleum bulk stations and terminals” used in the electricity and fuel-use part of the survey (Bureau of the Census*1987 Census of Wholesale Trade, Measures of Value Produced, Capital expenditures, Depreciable assets, and Operating Expenses,* 1991) is slightly different than the definition used in the gallon-sales part of the survey (Bureau of the Census, *1987 Census of Wholesale Trade, Miscellaneous Subjects,* 1991). Nevertheless, we use electricity and fuel use data from the *Measures of Value Produced...*report, and gallon data from the *Miscellaneous Subjects* report. We have scaled the reported gallon sales by the ratio of total sales to reported sales.

These energy use factors do not include diesel fuel used by tanker trucks.

[c] We assume that electricity and fuel use at service stations is proportional to the amount of liquid-fuel energy dispensed. (Fuel used for repair at service stations probably is more directly related to VMT. However, we assume that repair work accounts for a minority of the energy use at service stations.) In 1987, service stations in SIC 554 sold 87.26 billion gallons of fuel (Bureau of the Census, *1987 Census of Retail Trade, Measures of Value Produced, Capital expenditures, Depreciable assets, and Operating Expenses,* 1991). The gallon-sales data and the electricity and fuel-use expenditure data are from the same survey (Bureau of the Census, *The 1987 Census of Retail Trade,* 1991*)* and pertain to the same population of service stations. However, businesses in SIC 554 sell more than just highway fuels, repair services, and automotive supplies: in 1987, food, drinks, drugs, household merchandise, and other non-automotive goods were slightly more than 10% of the sales in SIC 554 (Bureau of the Census, *1987 Census of Retail Trade, Subject Series, Merchandise Line Sales,* 1990). On the assumption that people would buy these non-automotive products elsewhere if they did not drive, we deduct the product’s share of electricity and fuel usage, which we assume is equal to the products’ share of total sales. Therefore, we allocate 90% of electricity and fuel use at service stations (SIC 554, which includes truck stops) to the 87 billion gallons of fuel sold in this SIC in 1987.

These energy-use factors do not include diesel fuel used by tanker trucks.

[d] This is the difference between the total electricity consumed at gasoline service stations and the amount of electricity used to pump gasoline. We estimate that pumping-power consumption is about half of total power consumption at service stations. We assume that a CNG station would use the same amount of non-pumping energy per 10^6 BTU of CNG as a gasoline station does per 10^6 BTU of gasoline.

[e] We assume 0.022 BTU-electricity per BTU-CNG, on the basis of a revision of the analysis in DeLuchi (1993).

[f] We assume that the amount of electricity and fuel used at motor-vehicle dealerships, automotive parts stores, repair shops, parking lots, administrative buildings, and so on, is

related directly or indirectly to total vehicle miles of travel. In most cases, this is a reasonable assumption. For example, energy use by repair shops, parking lots, and most motor-vehicle services probably is proportional to VMT. Energy use at motor-vehicle dealerships probably is more directly related to the total numbers of vehicles sold, but VMT in turn probably is related to vehicle sales, and in any case is easier to work with.

Further on in the analysis, we estimate emissions attributable to these activities (motor-vehicle sales and service, etc.) by multiplying these energy-use factors by emission factors. We do this for alternative-fuel vehicles as well as for gasoline vehicles, on the assumption that alternative-fuel vehicles require the same amount of energy per mile for auto sales and support and so on as do gasoline vehicles.

[g] Our energy-use measure is: all energy associated with the sale of motor vehicles, the sale of motor-vehicle parts, and motor-vehicle repair done at motor-vehicle dealers and parts stores, in 1987, divided by total VMT of 1.9212 trillion in 1987 (FHWA, *Highway Statistics 1988*, 1989). The Census data for SIC 55 (except 554) of Table 9 do not cover *all* of this relevant energy use, because some motor vehicles and parts are sold in other industries (such as department stores). Furthermore, a small fraction of the sales in SIC 55 (except 554) are not related to motor-vehicle use. To account for both of these problems, we adjust electricity and fuel consumption by multiplying electricity and fuel consumption in SIC 55 (except 554) by the ratio of dollar sales of all automotive merchandise lines in all SICs (except 554) to dollar sales of all merchandise in SIC 55 (except 554). (1.034; from Delucchi, 1995b).

[h] We have multiplied energy consumption in SICs 751 and 754 by five, to account for the energy consumption of automobile insurance companies, highway maintenance and lighting, motor-vehicle departments, and police, fire, and justice departments. The factor of five is the ratio of expenditures in all of these areas to receipts in SICs 751 and 754.

[i] SIC 752 obviously does not include free commercial parking. Roughly 95% of all non-residential parking is free (Delucchi and Murphy, 1995). Therefore, we multiply energy consumption in SIC 752 by 20 to obtain energy consumption for all non-residential parking (energy consumption by residential, or non-commercial, parking is estimated separately, below), and divide by 1.9212 trillion total VMT in 1987 (FHWA, *Highway Statistics 1988*, 1989).

A calculation with a different data set yields a considerably higher result. In 1989, parking garages used a total of 5.33 kWh of electricity and 36.5 SCF of natural gas per square foot (Energy Information Administration, *Energy End-Use Intensities in Commercial Buildings*, 1994). Assuming 50 million spaces in parking garages, with a total floor area of 320 ft^2 per parking space (Delucchi and Murphy, 1995), and 2.1 trillion VMT in 1989 (FWHA, *Highway Statistics 1990*, 1991), the result is 0.04 kWh / VMT and 0.28 SCF / VMT -- for parking garages alone.

[j] Our energy-use measure is all energy associated with motor-vehicle repair in 1987, and not already included in SIC 55 (under motor vehicle dealers and service stations), divided by all 1.9212 trillion total VMT in 1987 (FHWA, *Highway Statistics 1988,* 1989). The Census data for SIC 753 in Table 9 do not cover *all* of this relevant energy use, because some motor vehicles are repaired by “in-house” repair shops at businesses, and some are repaired by households. We estimate energy use at home garages separately. That leaves energy use by repair activities done outside of SIC 75, SIC 55 and the home. On the basis of data in Delucchi

(1995c), we estimate that this “in-house” repair work not covered in SICs 75 or 55 is 10% of the amount done in SIC 75.

(Also, we assume that all of the business in SIC 75 is related to motor-vehicle use.)

[k] In 1990, households in the U.S. consumed 1.4 quads of electricity for lighting and appliances other than refrigerators, air conditioners, and water heaters (EIA, *Household Energy Consumption and Expenditures 1990*, 1993). We assume that on average a residential parking space occupies 10% of the total floor space of a house, and uses one-quarter as much electricity for lighting and appliances per square foot as does the whole house. We then assign 80% of the electricity use in these spaces to motor vehicles, and 20% to other uses such as storage and hobbies. Finally, we assume that residential (non-commercial) parking spaces are not heated, and hence do not consume natural gas or fuel oil. We divide the resulting electricity consumption by total VMT in 1990 (FHWA, *Highway Statistics 1991*, 1992).

An alternative calculation yields a comparable estimate. In 1989, commercial parking garages used an average 2.5 kWh per square foot for lighting (Energy Information Administration, *Energy End-Use Intensities in Commercial Buildings,* 1994). Residential parking spaces probably use much less; say, around 1.0 kWh per square foot (including electricity for garage door openers, and power tools for working on cars). Assuming 75 square feet of off-street, off-driveway, non-commercial parking per each of the 193 million passenger vehicles and light-trucks the U.S. in 1990 (FWHA, *Highway Statistics1991*, 1992), the result is 14.4 billion kWh in 1990, or 0.007 kWh / mile.

TABLE 11. CARB/EMFAC EMISSION FACTORS FOR REFORMULATED-GASOLINE AND DIESEL-FUEL VEHICLES, SUMMERTIME YEAR 2003

	LDA	LDT	Bus
NMOG exhaust[a] (g/mile)			
Incremental cold start	1.975	2.376	0
Incremental hot start	0.272	0.358	0
Stabilized running emissions	0.145	0.196	5.62
CO exhaust[a] (g/mile)			
Incremental cold start	21.790	33.740	0
Incremental hot start	4.740	6.870	0
Stabilized running emissions	2.490	3.030	25.47
NOx exhaust[a] (g/mile)			
Incremental cold start	1.490	2.250	0
Incremental hot start	0.810	1.190	0
Stabilized running emissions	0.310	0.440	19.86
NMOG evaporative[a]			
Hot soak (g / trip)	0.330	0.320	0
Diurnal (g / day)	0.530	0.540	0
Running loss (g / mile)	0.154	0.154	0
Resting loss (g / day)	0.960	0.840	0
Other emissions			
Exhaust PM[a] (g / mile)	0.010	0.010	2.45
Tire wear and brake wear PM_{10}[b] (g / mile)	0.22	0.22	0.66
N_2O (g / mile)[c]	0.050	0.050	0.02
CH_4 (fraction of exhaust NMOG)[c]	0.147	0.147	0.048
Drive cycle data and other data			
RVP of gasoline in EMFAC runs[a]	7.00	7.00	n.a.
Speed in EMFAC runs[a] (mph)	20.00	20.00	20.00
Bag-2 to Bag 1 speed correction[a] (multiplier)	0.81	0.79	n.a.
Distance of Bag-2 test (miles)[d]	3.89	3.89	n.a.
Distance of Bag-1 test (miles)[d]	3.59	3.59	n.a.
Fraction of exhaust TOG that is NMOG[e]	0.8515	0.8515	0.9573
Fraction of evaporative TOG that is NMOG[f]	1	1	n.a.

LDA = light-duty automobile; LDT = light-duty truck; TOG = total organic gases; NMOG = nonmethane organic gases; CO = carbon monoxide; NO_x = nitrogen oxides; PM = particulate matter; CH_4 = methane; N_2O = nitrous oxide.

[a] EMFAC estimated PM (not PM_{10}) emissions for catalyst-equipped LDAs and LDTs in summertime of the year 2003 (using year-2003 reformulated gasoline), with inspection and maintenance programs in place. For the final PM_{10} emission estimates, we multiply PM by the fraction that is PM_{10}. According to EPA's *Air Emissions Species Manual, Volume II* (1990), PM from gasoline vehicles is 97% PM_{10}, and PM from diesel-fuel vehicles is 100% PM_{10} (EPA *Air Emissions Species Manual, Volume II*, 1990). We assume that PM from AFVs is 97% PM_{10}.

[b] From CARB'sEMFAC7F and EPA's *Air Emissions Species Manual, Volume II* (1990). See text for relevant discussion.

[c] From DeLuchi (1991, 1993).

[d] The distances in the Federal Test Procedure.

[e] EMFAC estimates TOG, not NMOG. We analyzed ARB emissions data to determine the fraction of TOG that is NMOG.

[f] There is no methane in gasoline or diesel fuel.

TABLE 12. EMISSIONS FROM ALTERNATIVE-FUEL VEHICLES RELATIVE TO EMISSIONS FROM GASOLINE AND DIESEL-FUEL VEHICLES

	LDAs				LDTs				Buses			
	M85	LPG	CNG	E85	M85	LPG	CNG	E85	M85	LPG	CNG	E85
NMOG exhaust[a]	1.265	0.647	0.647	0.941	1.265	0.647	0.647	0.941	1.937	0.873	0.317	1.937
Reactivity of exhaust[b]	0.43	0.58	0.19	0.73	0.43	0.58	0.19	0.73	0.43	0.58	0.19	0.73
CO exhaust[a]	0.900	0.700	0.500	0.900	0.900	0.700	0.500	0.900	1.195	0.833	0.639	1.195
NOx exhaust[a]	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.600	0.500	0.500	0.600
NMOG evaporative[a]	0.43	0.00	0.00	0.20	0.43	0.00	0.00	0.20	input mass	input mass	input mass	input mass
Reactivity of evaporative[c]	0.16	0.13	0.00	0.41	0.16	0.13	0.00	0.41	0.16	0.13	0.00	0.41
PM exhaust[a]	0.50	0.30	0.20	0.50	0.50	0.30	0.20	0.50	0.20	0.15	0.10	0.20
PM tire-wear[d]	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
N2O exhaust[a]	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
CH4 exhaust[a]	0.50	1.00	20.00	0.50	0.50	1.00	20.00	0.50	0.50	1.00	30.00	0.50

Notes: see next page.

LDA = light-duty automobile; LDT = light-duty truck; TOG = total organic gases; M85 = 85% methanol and 15% gasoline; LPG = liquefied petroleum gases (mainly propane); CNG = compressed natural gas; E85 = 85% ethanol and 15% gasoline; NMOG = nonmethane organic gases; CO = carbon monoxide; NO_x = nitrogen oxides; PM = particulate matter; CH_4 = methane; N_2O = nitrous oxide.

Note that SO_x emissions are calculated on the basis of the sulfur content of the fuel.

[a] From DeLuchi (1991, 1993), or information therein. The estimates in this table pertain to single-fuel, optimized alternative-fuel vehicles. There is a huge literature on emissions from AFVs relative to emissions from GVs and buses. For example, U. S. Congress (1990), Heath (1992), Sperling and DeLuchi (1993), Webb (1992), and Gushee (1992) provide summaries.

Because diesel buses do not have appreciable evaporative emissions, we have estimated evaporative emissions from alternative-fuel buses directly, rather than relative to [the practically non-existent] evaporative emissions from diesel buses.

[b] The reactivity adjustment factors (RAF) for exhaust emissions are the “maximum incremental reactivity” factors calculated with the SAPRC90 mechanism (McNair et al., 1992; CARB, 1992), with two further modifications by us. First, we have increased the original factors for LPG, methanol, and ethanol by 10%, to account for an apparent underestimation of ozone-forming potential during extremely stagnant conditions (McNair et al., 1994). CARB in fact has officially increased the RAF for methanol by 10% on account of this. McNair et al. (1994) suggest that the same should be done for LPG, and we assume further that ethanol should be treated similarly to methanol (McNair et al. do not consider ethanol). It appears that the RAF for CNG need not be increased.

Second, we have increased all of the original RAFs to account for the lower reactivity of reformulated gasoline compared with the reactivity of the current industry-average gasoline with respect to which the original RAFs have been developed. That is, we divide the original RAFs (estimated relative to current industry-average gasoline) by the RAF for reformulated gasoline (estimated relative to the same current industry-average gasoline) to obtain RAFs for alternative fuels relative to reformulated gasoline. We assume an RAF for reformulated gasoline of 0.95 (California Air Resources Board, March 15 1993).

Note that the RAF for ethanol was developed on the basis of very little data (CARB, 1992). However, recent tests on four variable-fuel 1992 Chevrolet Luminas adjusted to run on ethanol have resulted in a similar albeit slightly higher RAF of 0.79 (Marshall, 1994; we have increased the reported factor of 0.68 by 10% [stagnant conditions] and then by 5% [versus reformulated gasoline], as discussed above).

[c] We assume that evaporative emissions from methanol vehicles comprise methanol, that evaporative emissions from LPG vehicles comprise propane, and that evaporative emissions from ethanol vehicles comprise ethanol. We then take Carter’s (1994) most recent RAFs (maximum incremental reactivity) for these compounds, and divide by our estimated 0.95 RAF for reformulated gasoline (see note b above).

[d] We assume that all vehicles will wear out tires at approximately the same rate.

TABLE 13. TOXIC AIR POLLUTANTS AS A FRACTION OF NMOG EMISSIONS FROM VEHICLES

	Gasoline exhaust[a]	M85[a]	LPG[b]	CNG[b]	E85[a]	Diesel[c]	Gasoline evaporation[d]
Benzene	0.039	0.010	0.001	0.001	0.006	0.011	0.030
Formaldehyde	0.017	0.053	0.041	0.014	0.018	0.029	0.000
Acetaldehyde	0.005	0.002	0.007	0.005	0.077	0.008	0.000
1,3-butadiene	0.004	0.001	0.000	0.001	0.001	0.014	0.000
Ethene	0.059	0.009	0.056	0.033	0.049	0.000	0.000

ex. = exhaust; evap. = evaporative emissions.

[a] These are fractions of composite FTP emissions of non-methane organic compounds. We calculated them from an emissions data base provided by CARB (Croes, 1995). The data base contained 41 tests on 12 Phase-II reformulated-gasoline TLEVs (transitional low-emission vehicles), 14 tests on 6 M85 TLEVs, 8 tests on 2 ethanol TLEVs, and 37 tests on 9 Phase-II reformulated-gasoline LEVs. The gasoline exhaust fractions are the averages of the fractions from the LEVs and the TLEVs.

Note that the emissions profile for E85 is based on only 8 emissions tests of 2 ethanol vehicles (Croes, 1995) -- far fewer vehicles and tests than for the other fuels. Consequently, the results for E85 are relatively uncertain.

[b] These are fractions of composite FTP emissions of non-methane organic compounds. We calculated them from an emissions data base provided by CARB (Purnell, 1995). The data base contained14 tests on 6 M85 TLEVs and 8 tests on 2 ethanol TLEVs.

[c] The results of tests on two heavy-duty diesel vehicles (EPA, *Motor Vehicle-Related Air Toxics Study*, 1993)

[d] From the EPA's (*Motor Vehicle-Related Air Toxics Study*, 1993) summary of studies of the benzene fraction of diurnal and hot-soak evaporative emissions from catalyst-equipped fuel-injected vehicles using reformulated gasoline. There are no toxic evaporative emissions other than benzene.

TABLE 14. CALCULATED LDA, LDT (VAN), AND BUS EMISSION FACTORS, CORRECTED FOR LOCAL TEMPERATURE, SPEEDS, AND TRIP DISTANCES (SACRAMENTO, BASELINE TRIP) (GRAMS/MILE)

	LIGHT DUTY AUTOMOBILES					**LIGHT DUTY TRUCKS**					**BUSES**				
Pollutant	*Gas*	*M85*	*LPG*	*CNG*	*E85*	*Gas*	*M85*	*LPG*	*CNG*	*E85*	*Diesel*	*M85*	*LPG*	*CNG*	*E85*
NMOG ex[a]	0.25	0.26	0.21	0.15	0.21	0.32	0.32	0.27	0.19	0.26	4.79	9.27	1.52	4.18	9.27
NMOG ev[b]	0.13	0.05	0.00	0.00	0.03	0.13	0.05	0.00	0.00	0.03	0.00	0.51	0.00	0.00	0.25
NMOG total RAF[c]	0.38	0.12	0.04	0.09	0.40	0.45	0.15	0.05	0.11	0.54	4.79	4.05	0.29	2.42	6.85
CO	4.76	2.64	3.77	3.16	3.04	6.39	3.84	4.79	4.22	4.31	20.13	24.06	12.87	16.78	24.06
NO_x	0.39	0.39	0.39	0.39	0.39	0.56	0.56	0.56	0.56	0.56	18.33	11.00	9.16	9.16	11.00
SO_x(d)	calculated on the basis of sulfur content					calculated on the basis of sulfur content					calculated on the basis of sulfur content				
PM_{10} ex[e]	0.01	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	2.45	0.48	0.24	0.36	0.48
PM_{10} tire, brake[e]	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.66	0.66	0.66	0.66	0.66
PM_{10} dust[f]	2.26	2.26	2.26	2.26	2.26	2.63	2.63	2.63	2.63	2.63	16.43	16.43	16.43	16.43	16.43
PM_{10} total[g]	2.49	2.48	2.48	2.48	2.48	2.86	2.85	2.85	2.85	2.85	19.54	17.57	17.33	17.45	17.57
C_6H_6	0.0119	0.0032	0.0003	0.0002	0.0014	0.0163	0.0037	0.0004	0.0003	0.0017	0.0513	0.0979	0.0021	0.0054	0.0571
HCHO	0.0045	0.0168	0.0085	0.0022	0.0042	0.0054	0.0199	0.0111	0.0028	0.0051	0.1408	0.5186	0.0626	0.0598	0.1713
CH_3CHO	0.0013	0.0006	0.0015	0.0008	0.0180	0.0016	0.0007	0.0020	0.0010	0.0217	0.0377	0.0196	0.0111	0.0226	0.7330
$CH_2CHCHCH_2$	0.0010	0.0002	0.0000	0.0001	0.0002	0.0013	0.0003	0.0000	0.0001	0.0003	0.0684	0.0068	0.0000	0.0021	0.0095
CH_2CH_2	0.0155	0.0028	0.0116	0.0050	0.0114	0.0189	0.0034	0.0151	0.0064	0.0138	0.0000	0.0881	0.0853	0.1380	0.4664
N_2O	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.02	0.02	0.02	0.02	0.02
CH_4	0.037	0.019	0.745	0.037	0.019	0.047	0.024	0.943	0.047	0.024	0.228	0.114	6.841	0.228	0.114

Notes: see next page.

LDA = light-duty automobile; LDT = light-duty truck; TOG = total organic gases; M85 = 85% methanol and 15% gasoline; LPG = liquefied petroleum gases (mainly propane); CNG = compressed natural gas; E85 = 85% ethanol and 15% gasoline; NMOG = nonmethane organic gases; CO = carbon monoxide; NO_x = nitrogen oxides; PM = particulate matter; C_6H_6 = benzene; ex = exhaust; ev = evaporative; HCHO = formaldehyde; CH_3CHO = acetaldehyde; $CH_2CHCHCH_2$ = 1,3-butadiene; CH_2CH_2 ethene; CH_4 = methane; N_2O = nitrous oxide.

See the text for an explanation of the calculation of these emission factors. As explained in the text, tailpipe emission factors for buses have been adjusted to account for the effect of any difference between the estimated fuel economy of the buses modeled here and the assumed fuel economy of the buses used to develop the EMFAC emission factors.

[a] Not adjusted for relative ozone reactivity.

[b] None of the totals shown here include diurnal emissions or resting loss emissions, because these emissions are not related to use of the vehicle -- they occur when the vehicle is idle. Also, the evaporative emissions shown here are not adjusted for ozone reactivity. Evaporative emissions from AF methanol and ethanol buses are estimated by multiplying estimated evaporative emissions from AF LDVs by the ratio of the mpg of the AFV LDV to the mpg of the AF bus.

[c] Adjusted for relative ozone reactivity.

[d] Calculated on the basis of the sulfur content of the fuel (Table 23), and the fuel efficiency of the vehicle (Table 1). We assume that all sulfur oxidizes to SO_2.

[e] Calculated from the values of Table 11. See text for further discussion. We assume that PM_{10} emissions from brake wear and tire wear are proportional to vehicle weight, and that the values of Table 11 correspond to a car with a loaded driving weight of 3200 lbs.

[f] Calculated using the EPA’s emission factor formula (AP-42, 1994), and the vehicle weights of Table 1. See text for further discussion.

[g] Exhaust emissions plus tire-and-brake-wear emissions plus paved-road-dust emissions.

TABLE 15. DISTRIBUTION OF TRAVEL BY PURPOSE, TYPE OF VEHICLE, AND TYPE OF ROAD

Road type[a]	**Travel by cars and vans**		**Travel by buses**		silt loading (g / m^2)[d]
	direct[b]	*access*[c]	*line haul*[b]	*access*[c]	
Interstates, freeways, expressways	0.22	0.10	0.25	0.10	0.022
Principal arterials	0.37	0.35	0.16	0.20	0.36
Minor arterials	0.21	0.25	0.16	0.20	0.64
Collectors	0.08	0.12	0.26	0.30	0.92
Local roads	0.13	0.18	0.17	0.20	1.41
Travel-weighted silt loadings (g / m^2)[e]	0.52	0.65	0.64	0.76	

[a] Categories in the FHWA’s (1993) road classification.

[b] We use FHWA (1993) data to estimate the fraction of travel on each type of road.

[c] We assume that most trips to transit stations are made entirely on local roads, collectors, and arterials.

[d] As mentioned in the text, the EPA (AP-42, 1994) summarizes 44 measurements of silt loading on local streets, collector streets, major streets and highways, and freeways and expressways. The EPA road classes correspond more or less to the FHWA’s local roads, collectors, principal arterials, and interstates and freeways and expressways. However, the FHWA category “minor arterial” appears to fall between the “collector streets” and the “major streets and highways” categories of the EPA. We have assumed that the silt loading on minor arterials is half way between the silt loading on EPA-designated “collector streets” and the loading on “major streets and highways”.

[e] Calculated with equation (10).

TABLE 16. ELFIN PROJECTIONS OF MARGINAL GENERATION, EFFICIENCY, AND EMISSIONS IN FOUR CALIFORNIA UTILITIES, YEAR 2003

	PG&E		LADWP[a]		SCE		SDG&E	
	Generation	*Imports*	*Generation*	*Imports*	*Generation*	*Imports*	*Generation*	*Imports*
Generation mix[b]								
San Francisco	0.929	0.071	0.000	0.000	0.000	0.000	0.000	0.000
Los Angeles	0.000	0.000	0.137	0.017	0.736	0.110	0.000	0.000
San Diego	0.000	0.000	0.000	0.000	0.000	0.000	0.908	0.092
Coal Boiler	0.002	0.200	0.000	0.430	0.005	0.439	0.000	0.463
Gas Boiler	0.892	0.000	1.000	0.296	0.586	0.307	0.203	0.338
Gas Turbine	0.024	0.000	0.000	0.000	0.068	0.000	0.005	0.000
Gas CC	0.087	0.000	0.000	0.000	0.352	0.000	0.792	0.000
Oil Boiler	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Biomass	0.004	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Nuclear	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Other	(0.028)	0.800	0.000	0.273	(0.011)	0.254	0.000	0.200
Efficiency								
Gas Boiler	0.347	n.e	0.339	n.e	0.330	n.e	0.273	n.e
Gas Turbine	0.250	n.e	n.e	n.e	0.208	n.e	n.e	n.e
Gas CC	0.455	n.e	n.e	n.e	0.397	n.e	0.484	n.e
ROG emissions *(lbs/10^6 BTU)*								
Gas Boiler	0.001	n.e	0.005	n.e	0.008	n.e	0.001	n.e
Gas Turbine	0.037	n.e	n.e	n.e	0.009	n.e	n.e	n.e
Gas CC	0.004	n.e	n.e	n.e	0.006	n.e	0.009	n.e
CO emissions *(lbs/10^6 BTU)*								
Gas Boiler	0.039	n.e	0.038	n.e	0.014	n.e	0.044	n.e
Gas Turbine	0.119	n.e	n.e	n.e	0.023	n.e	n.e	n.e
Gas CC	0.062	n.e	n.e	n.e	0.008	n.e	0.025	n.e
NO_x emissions *(lbs/10^6 BTU)*								
Gas Boiler	0.027	n.e	0.016	n.e	0.017	n.e	0.021	n.e
Gas Turbine	0.244	n.e	n.e	n.e	0.286	n.e	n.e	n.e
Gas CC	0.037	n.e	n.e	n.e	0.076	n.e	0.021	n.e

SO_x emissions *(lbs/10^6 BTU)*								
Gas Boiler	0.001	n.e	0.001	n.e	0.001	n.e	0.001	n.e
Gas Turbine	0.108	n.e	n.e	n.e	0.002	n.e	n.e	n.e
Gas CC	0.001	n.e	n.e	n.e	0.001	n.e	0.001	n.e
PM_{10} emissions *(lbs/10^6 BTU)*								
Gas Boiler	0.003	n.e	0.008	n.e	0.002	n.e	0.004	n.e
Gas Turbine	0.037	n.e	n.e	n.e	0.014	n.e	n.e	n.e
Gas CC	0.006	n.e	n.e	n.e	0.002	n.e	0.015	n.e

PG&E = Pacific Gas & Electric; LADWP = Los Angeles Department of Water and Power; SCE = Southern California Edison; SDG&E = San Diego Gas & Electric; CC = combined cycle; ROG = reactive organic gases (similar to nonmethane hydrocarbons); CO = carbon monoxide; NO_x = nitrogen oxides; SOx = sulfur oxides; PM_{10} = particulate matter of less than 10 micron diameter; n.e. = not estimated.

Source: The "Elfin" electricity model of the California Energy Commission (CEC), programmed to model the effect of a uniform 1% increase in electricity demand in 2003, compared to the Elfin base case. Of course, in reality the extra electricity demand of a new transit system will not simply bump up demand by 1% every hour, which is what Elfin modeled. For example, rail systems use more energy during peak hours than they do after the trains stop running for the night. Unfortunately, the CEC was not able to model a change in demand hour-by-hour. We note, though, that with rail systems the difference between peak and off-peak energy use might not be as large as one might expect, because nontraction energy use (e.g., for lighting stations) is independent of passenger load (and a large fraction of total energy use), and traction energy use is only weakly related to passenger load.

The data sets in the Elfin model represent typical conditions in a year. To the extent that conditions in the future are not like the "typical" conditions represented in Elfin, the Elfin output will be inaccurate. Also, the Elfin data sets include the CEC's projections of the *maximum* cost, not necessarily the most likely cost, of any additional resources required by utilities. Consequently, the Elfin output are not the CEC's official projections of capacity, emissions or fuel use.

[a] The California Energy Commission produced Elfin results for LADWP "before" the 1% increase in demand, but was unable to run the "after" scenario. In order to estimate the effects of the 1% increase in demand in LADWP, we assumed that: $\text{LADWP}_{\text{difference}}$ = $\text{LADWP}_{\text{before}}$ x $\text{SDG\&E}_{\text{difference}}$ / $\text{SDG\&E}_{\text{before}}$; that is, we scaled the LADWP before (or base case) factors by scaling factors (difference / before) from the SDG&E utility.

[b] The entries in the first three rows under "Generation mix" (San Francisco through San Diego) show the fraction of electricity consumption in each region that is supplied by in-service-area generation or imports by Utility. They total to 1.00 horizontally across all utilities. (Sacramento is not included here because the Elfin does not include the Sacramento Municipal Utility District.) The entries in the remaining rows (coal boiler to other) show the fraction of total generation by each utility that comes from each plant type. They total to 1.00 vertically.

[c] Includes geothermal power, hydropower (including srpingtime hydro spill), wind power, and solar power.

TABLE 17. PROJECTED FUEL INPUT AND ELECTRICITY GENERATION OF U.S. UTILITY AND NON-UTILITY POWER GENERATION

	1995		2000		2005		2010	
	quads	*tWh*	*quads*	*tWh*	*quads*	*tWh*	*quads*	*tWh*
Coal Boiler[a]	n.e.	1,641.5	17.5	1,696.0	18.02	1,748.0	19.93	1,936.0
Coal FBC[a]	n.e.	0.0	0.0	0.0	0.01	1.0	0.02	2.0
Coal IGCC[a]	n.e.	0.0	0.0	0.0	0.01	1.0	0.02	2.0
Gas Boiler[b]	n.e.	209.8	2.3	204.1	2.1	185.2	1.6	149.5
Gas Turbine[b]	n.e.	28.6	0.4	34.5	0.47	40.8	0.46	40.0
Gas CC[b]	n.e.	93.6	1.6	168.4	2.64	285.0	3.00	327.4
Oil Boiler[b]	n.e.	74.9	0.8	78.1	0.84	77.9	0.66	61.7
Oil Turbine[b]	n.e.	2.8	0.1	4.4	0.08	7.1	0.07	6.2
Oil CC[b]	n.e.	1.9	0.0	3.5	0.06	6.0	0.07	7.2
Biomass[c]	n.e.	n.e.	0.50	48.4	0.68	65.9	0.87	83.6
Nuclear	n.a	n.e.	n.a.	671.0	n.a	680.0	n.a	612.0
Other[d]	n.a	n.e.	n.a	314.6	n.a	327.1	n.a	370.4
Total	n.e.	n.e.	23.22	3,223.0	24.89	3,425.0	26.69	3,598.0

Source: Energy Information Administration, *Annual Energy Outlook 1994* (1994), *Supplement to the Annual Energy Outlook 1994* (1994), and unpublished data from the EIA Office of Integrated Analysis and Forecasting (1994); data on power generation and fuel input for power generation by utility and nonutility generators. Excludes cogeneration, except as noted.

tWh = terawatt-hour (10^{12} watt-hours); quad = 10^{15} BTUs; FBC = fluidized-bed combustion; IGCC = integrated gasification combined-cycle; CC = combined cycle; n.e. = not estimated; n.a. = not applicable

[a] The EIA shows generation for the generic category “coal,” and does not distinguish generating technologies. We estimate that FBC and IGCC coal technology comes on line in 2005.

[b] The EIA’s *Annual Energy Outlook 1994* (1994) and *Supplement to the Annual Energy Outlook 1994* (1994) project total generation by gas-fired plants and by oil-fired plants, but do not break down the projections by type of generating technology. However the EIA’s Office of Integrated Analysis and Forecasting (1994) provided us with their unpublished projections of generation by oil steam plants, gas steam plants, oil and gas dual-fuel steam plants, oil combustion turbines, gas combustion turbines, oil and gas dual-fuel combustion turbines, oil combined cycles, gas combined cycles, and oil and gas dual-fuel combined cycles. The EIA does not state what fraction of generation by dual-fuel plants comes from gas, and what

fraction comes from oil, so we must make assumptions ourselves: we assume that gas is used to generate 78% of the output of dual-fuel steam plants, 100% of the output of dual-fuel combustion turbines, and 98% of the output of dual-fuel combined-cycle plants. With these assumptions, our resultant total generation by all gas plants and total generation by all oil plants equals the EIA's (*Annual Energy Outlook 1994*, 1994) projection of total generation by gas plants and by oil plants.

The EIA's *Annual Energy Outlook 1994* (1994) and *Supplement to the Annual Energy Outlook 1994* (1994) project total consumption of coal, oil, gas, and biomass by utility and nonutility generators, but not for individual technologies. However, the EIA does project the energy efficiency of new generating technologies (EIA, *Supplement to the Annual Energy Outlook 1994*, 9194). We allocate total projected fuel consumption to individual generating technologies so that the back-calculated generation efficiencies are consistent with the EIA's efficiency projections.

[c] Biomass and wastes. Includes biomass-fueled cogeneration.

[d] All other utility and nonutility generation, including pumped storage *less* biomass-fueled cogeneration. We have subtracted biomass-fueled cogeneration so that the total matches the EIA's total projected utility and nonutility generation.

TABLE 18. PROJECTED U.S. NATIONAL AVERAGE GENERATION MIX AND EFFICIENCY

Year:	2000		2005		2010	
	mix	*efficiency*	*mix*	*efficiency*	*mix*	*efficiency*
Coal Boiler	0.526	0.331	0.510	0.331	0.538	0.331
Coal FBC	0.000	n.a.	0.000	0.371	0.001	0.379
Coal IGCC	0.000	n.a.	0.000	0.371	0.001	0.379
Gas Boiler	0.063	0.298	0.054	0.304	0.042	0.321
Gas Turbine	0.011	0.294	0.012	0.296	0.011	0.297
Gas CC	0.052	0.364	0.083	0.368	0.091	0.372
Oil Boiler	0.024	0.322	0.023	0.316	0.017	0.317
Oil Turbine	0.001	0.294	0.002	0.295	0.002	0.298
Oil CC	0.001	0.364	0.002	0.368	0.002	0.370
Biomass	0.015	0.330	0.019	0.331	0.023	0.328
Nuclear	0.208	n.a.	0.199	n.a.	0.170	n.a.
Other	0.098	n.a.	0.095	n.a.	0.103	n.a.

Source: Table 17. See the notes to that table. Excludes cogeneration, except as noted.

tWh = terawatt-hour (10^{12} watt-hours); quad = 10^{15} BTUs; FBC = fluidized-bed combustion; IGCC = integrated gasification combined-cycle; CC = combined cycle; n.a. = not applicable.

TABLE 19. CALCULATED AVERAGE GENERATION MIX FOR FIVE CALIFORNIA UTILITIES, 2003

	PG&E		SMUD		LADWP		SCE		SDG&E	
	Generation	*Imports*[b]	*Generation*	*Imports*[c]	*Generation*	*Imports*[d]	*Generation*	*Imports*[e]	*Generation*	*Imports*[f]
Sacramento	0.000	0.000	0.555	0.445	0.000	0.000	0.000	0.000	0.000	0.000
San Francisco	0.850	0.150	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Los Angeles	0.000	0.000	0.000	0.000	0.117	0.107	0.698	0.078	0.000	0.000
San Diego	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.948	0.052
Coal boiler	0.020[g]	0.200	0.000	0.200	0.446	0.450	0.191[g]	0.414	0.000	0.228
Gas boiler	0.3967	0.000[h]	0.000	0.000	0.330	0.320	0.343	0.269	0.552	0.000
Gas turbine	0.021	0.000	0.000	0.000	0.009	0.000	0.026	0.000	0.119	0.000
Gas CC	0.000	0.000	0.000	0.000	0.000	0.000	0.045	0.000	0.000	0.000
Oil boiler	0.009	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Biomass	0.060[g]	0.000	0.000	0.000	0.000	0.000	0.032[g]	0.000	0.010[i]	0.000
Nuclear	0.195	0.000	0.000	0.000	0.109	0.000	0.200	0.000	0.318	0.000
Other[j]	0.299	0.800	1.000	0.800	0.109	0.230	0.164	0.317	0.000	0.772

Source: We projected future generation on the basis of historical generation data and future capacity projections in the Biennial Electricity Report (ER) of the California Energy Commission (CEC) (1992). The CEC's ER shows actual annual generation (in Watt-hours), by fuel type and Utility, through 1991, and projects capacity (Watts) by fuel type and Utility for 1992 and later. Generation (in Watt-hours per year) is equal to capacity (in Watts) multiplied by of hours of operation per year. In essence, we calculated the number of hours that each fuel type (e.g., coal) in each Utility (e.g., PG&E) operated in 1991, and assumed that the same fuel type for the same Utility will operate the same number of hours in each future year. In order to calculate the number of hours of operation in 1991, we assumed that the actual capacity in 1991 was equal to the projected capacity in 1992. Also, because the CEC distinguishes between gas boilers and turbines and combined-cycle plants in its capacity projections but not in its historical generation figures, we in effect assumed that all gas-fired plants operate the same number of hours per year.

The entries in the first four rows (Sacramento through San Diego) show the fraction of electricity consumption in each region that is supplied by in-service-area generation or imports by Utility. They total to 1.00 horizontally across all five utilities. The entries in the remaining rows (coal boiler to other) show the fraction of total generation by each utility that comes from each plant type. They total to 1.00 vertically.

PG&E = Pacific Gas & Electric; SMUD = Sacramento Municipal Utility District; LADWP = Los Angeles Department of Water and Power; SCE = Southern California Edison; SDG&E = San Diego Gas & Electric.

[b] The ER projects capacity available to PG&E from the Pacific Northwest. We follow the suggestion of CEC staff and assume that 80% of this is hydro capacity, and 20% coal-fired capacity.

[c] The ER projects capacity available to SMUD from the Pacific Northwest and from other California Utilities. We assume that the capacity from the Pacific Northwest is 80% hydro and 20% coal, and that the capacity from other California Utilities comes from PG&E and SCE.

[d] The ER projects capacity available to LADWP from the Pacific Northwest and the Pacific Southwest. We follow the suggestion of CEC staff, and assume that the capacity from the Pacific Northwest is 80% hydro and 20% coal and that the capacity from the Pacific Southwest is 55% coal and 45% gas.

[e] The ER projects capacity available to SCE from the Pacific Northwest, the Pacific Southwest, and other California Utilities. We assume that the capacity from the Pacific Northwest is 80% hydro and 20% coal, that the capacity from the Pacific Southwest is 55% coal and 45% gas, and that the capacity from other California Utilities comes from PG&E.

[f] The ER projects capacity available to SDG&E from the Pacific Northwest, the Pacific Southwest, and Mexico. We assume that the capacity from the Pacific Northwest is 80% hydro and 20% coal, that the capacity from the Pacific Southwest is 55% coal and 45% gas, and that the capacity from Mexico is the same as that from the Pacific Southwest..

[g] The historical generation figures for 1991 distinguish biomass from coal, but the capacity projections lump biomass with coal (CEC, 1992). We have separated biomass from coal in our projections of generation by assuming that the future ratio of biomass to coal generation will be the same as it was in 1991.

[h] The ER projects that PG&E will get all of its out-of-state power from the Pacific Northwest -- which we assume will provide coal or hydro but no gas-fired capacity -- even though in 1991 PG&E got 8% of its total out-of-state imports from gas-fired plants in the Pacific Southwest (CEC, 1992). Because the actual consumption in 1991 is inconsistent with the projections, we used the actual consumption in1990, when PG&E got virtually all of its imported power from the Pacific Northwest, as the basis of our calculation of future generation given future capacity projections.

[i] In 1991, SDG&E generated 1% of its electricity from biomass, and none from coal (CEC, 1992). However, the CEC projects no coal/biomass capacity for 1993. We assumed 1% biomass-fired capacity in 1993, and reduced the CEC's projected oil-fired capacity by 1%.

[j] Includes geothermal power, hydropower (including srpingtime hydro spill), wind power, and solar power.

TABLE 20. PROJECTED MARGINAL GENERATION MIX FOR BOSTON AND WASHINGTON, D. C., YEAR 2000

	Boston	**Washington, D. C.**
Coal Boiler	0.10	0.60
Coal FBC	0.00	0.00
Coal IGCC	0.00	0.00
Gas Boiler	0.16	0.06
Gas Turbine	0.08	0.08
Gas Combined Cycle	0.10	0.02
Oil Boiler	0.40	0.10
Oil Turbine	0.10	0.06
Biomass	0.02	0.02
Nuclear	0.04	0.06
Hydro, geothermal, wind, etc.	0.00	0.00

Source: As a basis for projecting the marginal generation mixes for Boston and Washington in the year 2000, we first reviewed the estimated average mixes for these cities in 1988, and then calculated average mixes for the region in the year 2000.

1). DeLuchi (1993) analyzed an EIA computer printout of electricity generation by fuel type for every utility in the U.S. in 1988, and a directory of the service areas of U.S. electric utilities, and estimated that in Boston in 1988, 89% of the electricity was from oil-fired plants, and 11% from natural-gas fired plans, and that in Washington, D. C., 88% was from coal, 12% from oil, and 1% from natural gas.

2) We used data from the EIA (*Supplement to the Annual Energy Outlook 1994*, 1994) to calculate average generation mixes in the year 2000 in the regional electricity markets surrounding Boston (New England) and Washington, D. C. (the Southeast) (Table 21). In the future regional mixes there will be less coal and oil power, and more nuclear power, than in the city mixes in 1988. Part of this is due to a projected decline in the use of oil in New England, and a projected increase in the use of natural gas in the Southeast, between 1988 and 2000 (EIA, *Supplement to the Annual Energy Outlook 1994*, 1994), and part is due to fundamental differences between the city mixes and the regional mixes.

On the basis of these estimates and considerations, and with the additional knowledge that nuclear and hydro power plants typically supply the baseload and not the margin, we projected the marginal power mixes of this table.

TABLE 21. PROJECTED AVERAGE GENERATION MIX FOR NEW ENGLAND AND THE SOUTHEAST, YEAR 2000

	New England[a]		**Southeast**[b]	
	generation (10^9 kWh)	*shares*	*generation (10^9 kWh)*	*shares*
Coal Boiler	16.65	0.158	332.02	0.566
Coal FBC	0.00	0.000	0.00	0.000
Coal IGCC	0.00	0.000	0.00	0.000
Gas Boiler	8.95	0.085	4.74	0.008
Gas Turbine	2.03	0.019	12.41	0.021
Gas Combined Cycle	4.10	0.039	0.12	0.000
Oil Boiler	15.92	0.151	0.40	0.001
Oil Turbine	3.05	0.029	1.38	0.002
Oil Combined Cycle	0.08	0.001	0.05	0.000
Biomass	2.06	0.019	2.06	0.004
Nuclear	41.82	0.396	197.68	0.337
Hydro, geothermal, wind, etc.	10.86	0.103	35.77	0.061
Total	**105.53**	**1.00**	**586.63**	**1.00**

Source: calculated from projections of generation and capacity in the EIA's *Supplement to the Annual Energy Outlook 1994* (1994).

[a] Maine, Vermont, New Hampshire, Massachusetts, Connecticut, and Rhode Island.

[b] Georgia, Alabama, South Carolina, North Carolina, Tennessee, Washington D. C., and parts of Mississippi, Kentucky, and Virginia.

TABLE 22. PROJECTED NATIONAL-AVERAGE EMISSIONS FROM ELECTRICITY-GENERATING PLANTS, WITH EMISSION CONTROLS, YEAR 2000 (LBS-EMISSION PER MILLION BTU INPUT)

	Coal DBPCB[a]	*Coal IGCC*[b]	*NG boiler*[a]	*NG turbine*[a]	*NG CC*[b]	*Fuel-oil boiler*[a]	*Biomass*[c]
CH_4	0.001	0.002	0.000	0.024	0.035	0.002	0.001
N_2O	0.009	0.009	0.004	0.004	0.004	0.004	0.009
NMHC	0.003	0.003	0.001	0.004	0.006	0.005	0.282
CO	0.029	0.004	0.039	0.110	0.112	0.033	0.066
NO_x(d)	0.502	0.095	0.267	0.220	0.201	0.336	0.082
SO_x(e)	0.923	0.075	0.001	0.001	0.001	0.529	0.009
PM	0.048	0.010	0.003	0.014	0.003	0.022	0.020
PM_{10}(f)	0.034	0.010	0.003	0.013	0.003	0.018	0.016
C_6H_6	0.0001	0.0001	0.0000	0.0015	0.0002	0.0050	0.0004
HCHO	0.0002	0.0002	0.0001	0.0030	0.0003	0.0021	0.0007
CH_3CHO	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	0.0003
$CH_2CHCHCH_2$	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.
CH_2CH_2	0.0000	0.0000	n.e.	n.e.	n.e.	n.e.	n.e.

DBPCB = dry-bottom pulverized-coal boiler (most utility power plants are of this type); IGCC = integrated gasification combined-cycle power plant; CC = combined cycle; CH_4 = methane; N_2O = nitrous oxide; NMHC = nonmethane hydrocarbons; CO = carbon monoxide; NO_x = nitrogen oxides; NO_2 = nitrogen dioxide; SOx = sulfur oxides; PM_{10} = particulate matter with a diameter of 10 microns or less; $PM_{2.5}$ = particulate matter with a diameter of 2.5 microns or less, C_6H_6 = benzene, HCHO = formaldehyde, $CH_2CHCHCH_2$ = 1,3-butadiene, CH_2CH_2 = ethylene, n.e. = not estimated.

[a] Emission factors for CH_4 and N_2O are from DeLuchi (1993). Emission factors for NMHCs, CO, NO_x, SO_x, PM, and PM_{10} are from the EPA's AP-42 (EPA, 1994) and other sources, as documented in DeLuchi (1993). Emission factors for toxic air pollutants are from the EPA's AP-42 (1994), *Air Emissions Species Manual* (1990) and *Toxic Air Pollutant Emission Factors* (1990), and are used as follows. The *Air Emissions Species Manual* (1990) reports formaldehyde emissions from oil boilers, formaldehyde and benzene emissions from natural-gas boilers, and ethylene and benzene emissions from industrial coal boilers, as a fraction of total VOC emissions. We assume that the fractions estimated for natural-gas boilers apply to natural-gas turbines and combined-cycle plants, and that the fraction estimated for coal boilers applies to coal IGCC plants. *Toxic Air Pollutant Emission Factors* (1990) reports a formaldehyde emission factor for coal boilers; we assume that this factor applies to coal-fired IGCC plants as well.. Finally, AP-42 (1994) reports emission factors for benzene, formaldehyde, and acetaldehyde

from wood-waste combustion. We assume that these factors apply to biomass power generation.

[b] Emission factors for CH_4, N_2O, NMHCs, CO, and NO_x are from DeLuchi (1993). The PM and PM_{10} factors are our estimates.

[c] The NMHC, CO, and NO_x emission factors are calculated from emissions data reported for a fluidized-bed power plant in Fresno, California (Ismail and Quick, 1992). The CH_4 and PM emission factors are from the EPA (1994), assuming an electrostatic precipitator to control PM. The N_2O emission factor is our estimate.

[d] As NO_2.

[e] SO_x emissions are calculated on the basis of the sulfur content of the fuel (Table 23). The SO_x emission factor for fuel-oil combustion includes emissions of SO_3 as well as of SO_2.

[f] The fraction of PM that is PM_{10} depends on the type of control technology used. Data in EPA's AP-42 (1992) indicate that 70% of the PM from coal boilers, 95% from natural-gas boilers, and 80% from oil and wood boilers, is PM_{10}.

TABLE 23. CHARACTERISTICS OF FUELS.

	Higher heating values				**Density**		**Carbon**	**Sulfur**
	Value	*Units*	*Value*	*Units*	*Value*	*Units*	*weight percent*	*weight percent*
Residual fuel	0.1497	10^6 BTU / gal	6.287	10^6 BTU / bbl	3575	g / gal	85.8	0.9900
Diesel fuel	0.1387	10^6 BTU / gal	5.825	10^6 BTU / bbl	3192	g / gal	85.8	0.05
Gasoline	0.1251	10^6 BTU / gal	5.253	10^6 BTU / bbl	2791	g / gal	86.6	0.004
Methanol	0.0645	10^6 BTU / gal	46446	g / 10^6 BTU	2996	g / gal	37.5	0.0007
Ethanol	0.0846	10^6 BTU / gal	35319	g / 10^6 BTU	2988	g / gal	52.2	0.0007
Coal			20.923	10^6 BTU / ton			60.0	0.9900
Hydrogen	7470	g / 10^6 BTU	338	BTU / SCF			0.0	0.0000
Natural gas	19768	g / 10^6 BTU	1032	BTU / SCF			0.0	0.0007
Dried wood			8350	BTU / lb				

Source: DeLuchi (1993), except sulfur content of gasoline, which is from Fletcher and Donohue (1992).

TABLE 24. EMISSIONS FROM THE USE OF ELECTRICITY IN CALIFORNIA (G/KWH-DELIVERED)

	Sacramento	**San Francisco**	**Los Angeles**	**San Diego**
NMHC	0.0014	0.0111	0.0317	0.0241
CO	0.0134	0.1950	0.0907	0.1263
NO_X	0.2321	0.2377	0.4561	0.2393
SO_X	0.4267	0.1736	0.2884	0.2080
PM_{10}	0.0155	0.0234	0.0283	0.0494
C_6H_6	0.0001	0.0004	0.0009	0.0005
HCHO	0.0001	0.0009	0.0018	0.0010
CH_3CHO	0.0000	0.0000	0.0000	0.0000
$CH_2CHCHCH_2$	0.0000	0.0000	0.0000	0.0000
CH_2CH_2	0.0000	0.0000	0.0000	0.0000
N_2O	0.0041	0.0209	0.0226	0.0185
CH_4	0.0007	0.0150	0.0480	0.0859
Fuelcycle greenhouse gases	108.80	648.07	700.68	577.20

NMHC = non-methane hydrocarbons, CO = carbon monoxide, NO_X = nitrogen oxides, SO_X = sulfur oxides, PM = particulate matter, PM_{10} = particulate matter with a diameter of 10 microns or less, $PM_{2.5}$ = particulate matter with a diameter of 2.5 microns or less, C_6H_6 = benzene, HCHO = formaldehyde, $CH_2ChCHCH_2$ = 1,3-butadiene, CH_2CH_2 = ethylene, N_2O = nitrous oxide, CH_4 = methane.

The emission factors are calculated from several data sets, as summarized below:

	Sacramento	San Francisco	Los Angeles	San Diego
Generation mix	average mix in 2003 (Table 19)	marginal mix in 2003 (Table 16)		
Efficiency and NMHC, CO, NO_X, SO_X, and PM_{10} emission factors, gas-fired power plants	not applicable	Elfin projections of marginal plant efficiency and emission factors for the year 2003 (Table 16)		
Efficiency and emission factors, all other pollutants, power plants	Our projections of U.S. national average efficiency (Table 18).and emission factors (Table 22), year 2000			

TABLE 25. EMISSIONS OF CRITERIA POLLUTANTS FROM PETROLEUM REFINERIES IN CALIFORNIA (GRAMS/GALLON OF OUTPUT)

	TOG	**ROG**	**CO**	**NO_X**	**SO_X**	**PM**	**PM_{10}**
Gasoline							
fuel use[a]	0.087	0.037	0.276	0.932	0.161	0.085	0.083
electricity use[b]	0.007	0.007	0.035	0.267	0.270	0.011	0.005
other process areas[c]	0.800	0.621	0.092	0.193	0.611	0.112	0.061
Total	*0.894*	*0.664*	*0.403*	*1.393*	*1.042*	*0.207*	*0.150*
Diesel fuel							
fuel use[a]	0.034	0.014	0.109	0.367	0.063	0.033	0.033
electricity use[b]	0.003	0.003	0.014	0.105	0.106	0.004	0.002
other process areas[c]	0.582	0.452	0.092	0.193	0.724	0.112	0.061
Total	*0.619*	*0.469*	*0.214*	*0.665*	*0.894*	*0.149*	*0.096*
Residual fuel oil							
fuel use[a]	0.027	0.012	0.087	0.292	0.051	0.027	0.026
electricity use[b]	0.002	0.002	0.011	0.084	0.085	0.003	0.002
other process areas[c]	0.386	0.300	0.092	0.193	0.055	0.110	0.060
Total	*0.415*	*0.313*	*0.189*	*0.569*	*0.191*	*0.140*	*0.088*

TOG = total organic gases; ROG = reactive organic gases; CO = carbon monoxide; NO_X = nitrogen oxides; SO_X = sulfur oxides; PM = particulate matter; PM_{10} = particulate matter with a diameter of 10 microns or less.

[a] Gram / gallon emissions from the use of refinery fuel are calculated with the following equation:

$$E_{fip} = \frac{T_{fi} \times C_{fi} \times F_p \times 365 \times 2000 \times 453.6}{O_p \times 42}$$

where:

Ef_{ip} = gram emissions of pollutant i from refinery fuel used to produce a gallon of product p

T_{fi} = emissions of pollutant i from the use of fuel at refineries in California in 1989 (tons / day; CARB, *Emission Inventory 1989*, 1991)

C_{fi} = projected emission control factor for boilers (g / gallon emissions of pollutant i in 2000 divided by g / gallon emissions of pollutant i in 1989 (1.0 for TOG, ROG, and CO; 0.75 for NO_X, SO_X, and PM)

F_p = BTUs of refinery energy used to make product p in the year 2000 divided by total BTUs of refinery energy consumed in 1991 (0.691 for gasoline, 0.148 for distillates, and 0.041 for residual fuel; calculated from data on gallon output of all products from California refineries [EIA, data transmittal, 1993] and the amount of energy required to make a gallon of each product [DeLuchi et al., 1992].

O_p = Output of product p from California refineries, 1991 (barrels; EIA, data transmittal, 1993; we use 1991 rather than 1989 data to match with the 1991 data on electricity use by California refineries).

365 = days / year

2000 = lbs / ton

453.6 = grams / lb

42 = gallons / barrels

[b]Gram / gallon emissions from the use of purchased electricity are calculated with the following equation:

$$E_{eip} = \frac{\left(G_{i-LA} \times S_{LA} + G_{i-SF} \times \left(1 - S_{LA}\right)\right) \times K \times F_p \times 2000}{O_p \times 42}$$

where:

E_{eip} = gram emissions of pollutant i from electricity purchased to produce a gallon of product p

$G_{i\text{-}LA}$ = g / kWh emissions of pollutant i from electricity plants supplying Los Angeles (Table 24)

S_{LA} = Refining capacity in Los Angeles area divided by refining capacity in state at the beginning of 1991 (0.608; calculated from data in the EIA's *Petroleum Supply Annual 1990*, 1991; we assume that the rest of the capacity is in the San Francisco area)

$G_{i\text{-}SF}$ = g / kWh emissions of pollutant i from electricity plants supplying San Francisco (Table 24)

K = kWh of electricity bought by California refineries in 1991 (EIA, data transmittal, 1993; data for 1989 are not available; we assume that the same amount was bought in 1989)

F_p = BTUs of refinery energy used to make product p in the year 2000 divided by total BTUs of refinery energy consumed in 1991 (0.691 for gasoline, 0.148 for distillates, and 0.041 for residual fuel; calculated from data on gallon output of all products from California refineries [EIA, data transmittal, 1993] and the amount of energy required to make a gallon of each product [DeLuchi et al., 1992].

O_p = Output of product p from California refineries, 1991 (barrels; EIA, data transmittal, 1993; we use 1991 rather than 1989 data to match with the 1991 data on electricity use by California refineries).

42 = gallons / barrels

[c]Gram / gallon emissions from process areas at refineries are calculated with the following equation:

$$E_{aip} = \frac{T_{ai} \times C_{ai} \times A_p \times 365 \times 2000 \times 453.6}{O_p \times 42}$$

where:

E_{aip} = gram emissions of pollutant i from process areas used to produce a gallon of product p

T_{ai} = emissions of pollutant i from process areas at refineries in California in 1989 (tons / day; CARB, *Emission Inventory 1989*, 1991)

C_{ai} = projected emission control factor for process areas (g / gallon emissions of pollutant i in 2000 divided by g / gallon emissions of pollutant i in 1989 (0.8 for TOG and ROG, 1.0 for CO and NO_X, and 0.9 for SO_X, and PM)

A_p = fraction of process-area emissions of pollutant i attributable to product p (DeLuchi et al., 1992)

O_p = Output of product p from California refineries, 1991 (barrels; EIA, data transmittal, 1993; we use 1991 rather than 1989 data to match with the 1991 data on electricity use by California refineries*)*.

365 = days / year

2000 = lbs / ton

453.6 = grams / lb

42 = gallons / barrels

TABLE 26. EMISSIONS OF TOXIC AIR POLLUTANTS FROM CALIFORNIA PETROLEUM REFINERIES (G/GALLON-OUTPUT)

	C_6H_6	HCHO	CH_3CHO	$CH_2CH\text{-}CHCH_2$	CH_2CH_2
Gasoline	0.0085	0.0077	0.0059	0.0069	0.0056
Diesel fuel	0.0043	0.0037	0.0024	0.0031	0.0022
Residual fuel oil	0.0032	0.0028	0.0019	0.0024	0.0018

Emissions of each toxic air pollutant are calculated as:

$$Et = \frac{Yt}{Yv} \times Ct \times (Vf + Vp) + Pt$$

where:

Et = Per-unit emissions of toxic air pollutant (grams / gallon)
Yt = Emissions of toxic air pollutant in SIC 2911 in 1989 (lbs / year; Table 12)
Yv = Emissions of volatile organic compounds in SIC 2911 in 1989 (lbs / year; CARB, *Emission Inventory 1989*, 1991)
Ct = Control factor for toxic pollutants specifically, on top of control of VOCs generally (assumed to be unity; i.e., no additional control)
Vf = Unit emissions (g / gal) of VOCs from fuel combustion (Table 25)
Vp = Unit emissions (g / gal) of VOCs from process areas (Table 25)
Pt = g / gallon emissions of toxic air pollutants from the generation of electricity bought by refineries

TABLE 27. EMISSIONS FROM THE PRODUCTION OF METHANOL AND ETHANOL (GRAMS/10^6 BTU OF OUTPUT)

Fuel--> *Feedstock->*	**MeOH** *mix*[a]	**EtOH** *mix*[a]	**MeOH** *NG*	**MeOH** *coal*	**MeOH** *wood*	**EtOH** *corn & coal*[c]	**EtOH** *corn & biomass*[b]	**EtOH** *wood*
NMHC	25.70	233.78	0.45	149.94	69.12	289.97	334.89	9.00
CO	8.22	14.29	6.00	12.96	16.16	4.62	10.65	53.00
NO_x	41.75	70.06	45.00	50.04	20.00	80.08	13.14	30.00
SO_x	5.35	118.41	0.15	50.00	1.60	147.01	1.42	4.00
TSP	n.e.	n.e.	0.15	10.00	10.00	15.67	11.59	20.00
PM_{10}(c)	1.98	12.40	0.14	7.50	7.50	11.76	8.69	15.00

MeOH = methanol; EtOH = ethanol; NG = natural gas; NMHC = nonmethane hydrocarbons; CO = carbon monoxide; NO_x = nitrogen oxides; SO_x = sulfur oxides; TSP = total suspended particulates; USDOE = U.S. Department of Energy; n.e. = not estimated.

Each g / gallon emission factor is calculated as:

$$G = \left(Ef \times C + \frac{P}{293.1} \times Ep \right)$$

where:

G = gram / gallon emission factor

Ef = emission factor in grams / 10^6-BTU fuel input (from USDOE, 1983; USDOE, 1988; Sperling , 1988; Intech, 1990; Heath, 1991; DeLuchi, 1991, 1993; Ecotraffic AB, 1992; Ismail and Quick, 1991; National Renewable Energy Laboratory, 1992; Tellus Institute, 1993; Darrow, 1994; EPA, 1994)

C = Conversion efficiency BTUs-input feedstock / BTUs-output product (NG / methanol, 1.5; coal / methanol, 1.8; wood / methanol, 1.6; coal / corn-ethanol, 0.53; biomass / corn-ethanol, 0.53; wood / ethanol, 2.35; see DeLuchi, 1993)

P = purchased power in BTUs-electricity / BTU-product (NG / methanol, 0.003; coal / methanol, 0; wood / methanol, 0.03; coal / corn-ethanol, 0.05; biomass / corn-ethanol, 0.05; wood / ethanol, -0.08; see DeLuchi, 1993)

293.1 = kWh per 10^6 BTUs

Ep = emissions from electricity generation in grams / kWh (generic out-of-state emission factors)

Note that the emission factors for NMHCs, CO, and NO_x are the same as the ones used in the greenhouse-gas analysis.

[a] Assuming the mix of feedstocks indicated in note b of Table 2.

[b] We estimated total emissions from the ethanol facility, and then allocated 67% of the total to fuel ethanol (DeLuchi, 1993). The remaining 33% is allocated to other products of the ethanol facility.)

[c] We assume that PM_{10} is 95% of TSP from NG-to-methanol plants and 75% of TSP from all other plants.

TABLE 28. EVAPORATIVE EMISSIONS FROM FUEL STORAGE, TRANSFER, DISTRIBUTION, AND DISPENSING (G/GALLON)

	Sacramento	**San Francisco**	**Los Angeles**	**San Diego**
Refueling emissions	3.48	2.06	2.31	2.37
Refueling spillage emissions	0.219	0.219	0.219	0.219
Other upstream emissions, excluding refineries	3.2	3.2	3.2	3.2
Total emissions, for gasoline	*6.90*	*5.48*	*5.72*	*5.78*
Total, for methanol	1.79	1.43	1.49	1.50
Total, for ethanol	1.10	0.88	0.92	0.93

Gasoline-cycle emissions are calculated as a function of temperatures and gasoline RVP, using equations from DeLuchi et al. (1992). We assume an RVP of 7.0 for gasoline (the value used in the EMFAC model), and the following temperatures:

	Sacramento	San Francisco	Los Angeles	San Diego
Average daily high temperature (July)	93.2	71.6	75.3	76.2
Average daily low temperature (July)	58.1	53.9	62.8	65.7
Temperature of dispensed fuel	79.2	60.9	64.0	64.8
Temperature of fuel in tank	88.5	68.0	71.5	72.4

The average high and low temperatures are from the Bureau of the Census, *Statistical Abstract of the United States* (1992).

We follow DeLuchi (1991) and assume that methanol-cycle emissions are 26% of gasoline cycle emissions, and ethanol-cycle emissions 16%.

TABLE 29. EMISSION FACTORS FOR NATURAL GAS AND DIESEL-FUEL USE BY BUILDINGS AND FUEL USE BY SERVICE VEHICLES

	Buildings[a]		**Service vehicles**[b]	
Pollutant	Natural gas *(g/1000 SCF)*	Fuel oil *(g/gallon)*	Diesel fuel *(g/gallon)*	Gasoline *(g/gallon)*
NMVOCs, vehicles	n.a.	n.a.	10.17	13.03[d]
NMOVCs, upstream	n.e	n.e.	0.00	4.00
NMOVCs, total	*3.30*[c]	*0.32*	*10.17*	*9.03*
CO	18.16	2.27	44.60	74.63
NO_x	42.68	8.17	35.67	7.65
SO_2(e)	0.29	70.79	2.87	0.22
PM_{10} exhaust	2.54	0.61	2.98	0.16
PM_{10} tire, brakewear	n.a.	n.a.	7.30	8.45
PM_{10} road dust	n.a.	n.a.	118.56	49.28
PM_{10}(f) total	*2.54*	*0.61*	*128.84*	*57.89*
C_6H_6	2.339	n.e.	0.00	0.46
HCHO	2.339	n.e.	0.87	0.09
CH_3CHO	2.339	n.e.	0.29	0.06
$CH_2CHCHCH_2$	2.339	n.e.	0.00	0.02
CH_2CH_2	2.339	n.e.	0.00	0.56
N_2O	2.063[g]	n.e.	0.06	1.00
CH_4	1.70[c]	0.81	0.48	0.68
GHGs from end use[h]	56,078	11,295	10,240	8,742
GHGs upstream[i]	9,809	2,070	2,047	2,784
Total GHGs	*65,887*	*13,365*	*12,287*	*11,525*

n.e. = not estimated; GHGs = greenhouse gases.

[a] Emission factors for NMVOCs, CO, NO_x, PM, and PM_{10} are EPA (*Compilation of Air Pollutant Emission Factors, Volume 1: Stationary Point and Area Sources* , 1994) factors for uncontrolled residential furnaces. Factors for toxic air pollutants are those used here for natural-gas-fired utility boilers (Table 22), converted to g / 1000-SCF.

[b] Emissions from the gasoline and diesel service and administrative vehicles used by transit systems are calculated in the same way as are the emissions from all of the other passenger cars and vans and buses considered in this analysis (see the text for details, and for example

the results of Table 14). (We assume national average temperatures and trip characteristics for the service vehicles here.) They include evaporative emissions, and account for emissions from cold starts and hot starts. Emissions of toxic air pollutants are calculated as a fraction of NMVOC exhaust emissions from diesel vehicles (data of Table 13). Gram / mile emission factors are converted to the g / gal factors of this table by multiplying by miles / gallon (mpg). We assume 7 mpg for diesel vehicles, and 20 mpg for gasoline vehicles (the average fuel economy of vehicles in large Federal fleets, according to the General Services Administration, 1994?). We use g / gal factors in this table, rather than g / mile factors, because the reported activity data are gallons of fuel consumed, not miles of travel.

[c] Emission factors for uncontrolled commercial boilers (EPA, AP-42, 1994).

[d] Includes our estimate of 0.06 g / mile resting and diurnal losses: 2 grams / day (from EMFAC7F) x 365 days / year divided by an assumed13,000 miles / year (average yearly travel of vehicles in large Federal fleets, according to the General Services Administration, 1994?).

[e] SO_2 emissions are calculated on the basis of the sulfur content of the fuel (Table 23), on the assumption that all fuel sulfur oxidizes to SO_2.

[f] The PM_{10} emission factors for natural gas and fuel oil combustion are the average of "filterable PM" and "condensible PM". According to EPA, all PM from natural-gas combustion is $PM_{1.0}$ or less.

The EPA (AP-42, 1994) does not show the distribution of the size of PM emissions from residential furnaces. However, it does show the size distribution of PM emissions from commercial fuel-oil boilers. We assume that this distribution applies to PM emissions from residential heaters.

[g] We assume the same emission rate as from natural-gas-fired utility boilers (Table 22; factors converted to g / 1000-SCF). N2O NG

[h] Emissions from motor vehicles are calculated by the equation below. Emissions from natural gas and oil heaters are calculated with similar equations.

$$G = E_{NMOG} \times C_{NMOG} \times \left(G_{NMOG} - 3.667\right) + E_{CO} \times \left(G_{CO} - 0.429 \times 3.667\right) +$$
$$E_{CH4} \times \left(G_{CH4} - 0.75 \times 3.667\right) + E_{NOx} \times G_{NOx} + E_{N2O} \times G_{N2O} + C \times D \times 3.667$$

Where:

G = CO_2-equivalent emissions from gasoline or diesel vehicles (g / 10^6-BTU)

E_{NMOG} = emissions of NMOG from vehicles (g / 10^6-BTU; this table)

C_{NMOG} = carbon fraction of NMOG emissions from gasoline or diesel-fuel vehicles (0.85 for gasoline, 0.86 for diesel fuel; DeLuchi, 1993)

G_{NMOG} = global warming potential of NMOG emissions (Table 34)

3.667 = ratio of mass of CO_2 to mass of C

E_{CO} = emissions of CO from vehicles (g / mile; this table)

G_{CO} = global warming potential of CO emissions (Table 34)
0.429 = carbon fraction of CO
E_{CH4} = emissions of CH_4 from vehicles (g / mile; this table)
G_{CH4} = global warming potential of CH_4 emissions (Table 34)
0.75 = carbon fraction of CH_4
E_{NOx} = emissions of NO_x from vehicles (g / mile; this table)
G_{NOx} = global warming potential of NO_x emissions (Table 34)
E_{N2O} = emissions of N_2O from vehicles (g / mile; this table)
G_{N2O} = global warming potential of N_2O emissions (Table 34)
C = carbon fraction of reformulated gasoline or diesel fuel (Table 23)
D = energy content of reformulated gasoline or diesel fuel (g / gal, Table 23)

[i] These are the upstream greenhouse-gas emission factors of Table 31, multiplied by 10^6-BTU / gal.

TABLE 30. EMISSION OF TOXIC AIR POLLUTANTS IN CALIFORNIA IN 1989 (LBS)

	Toxic ID number -->	1110	1210	50000	67561	71432	75070	106990	108883	7439921
SIC	Industry	Gas Vapors	Xylenes	Formal-dehyde	Methanol	Benzene	Acetal-dehyde	1-3 Butadiene	Toluene	Lead
1311	Crude petroleum & natural gas	10,101	115,787	247,130	38,583	231,460	22,430	2,699	136,554	219
1381	Drilling & oil & gas wells		21	427	431	64	16		33	
1382	Oil / gas exploration services			1,396		141				
1389	Oil / gas field services, n.e.c.	3,503	96	188		568			844	0
2911	Petroleum refining	3,439,271	956,819	147,825	12,805	199,829	19,486	87,748	491,957	1,712
3711	Motor vehicle & car bodies	934	336,348	874	6,774	13			65,005	
3713	Truck and bus bodies		169,130	1,130	17,000	21			505	
3714	MV parts / accessories		59	980		0	5,591		917	
3715	Truck trailers		43,495		55				424	341
3716	motor-home manufacturing	1,301	5,518		3,463				17,778	
4491	Marine cargo handling	179								
4911	Electric services	3,627	16,395	966,501		54,215	2,080	1,323	31,766	9,033
5171	Petrol bulk stations / terminals	3,160,208	44,278	45	6,696	26,630	1		67,993	0
5172	Petrol products, n.e.c.	74,295	1,076		841	799			4,711	
5511	New & used car dealers	34	16,746			0			9,505	
5521	Used car dealers		86						9	
5541	Gasoline services stations	7,289	99			93			403	
7531	Top & body repair shops		8,479	0		31			28,889	1
7532	Top & body repair / paint shops	172	90,615	0	656	14			115,711	2
7533	Auto exhaust-system repair shops		1,066		278				2,815	
7534	Tire retreading & repair shops			1	4,355	270			2,843	
7535	Paints shops		1,029			0			3,484	
7538	General Auto Repair shops		502			0			3,721	
7539	Auto Repair shops, n.e.c.		117			2			347	0
7542	Car washes			3		1			38	0

Notes: see next page.

Source: The Special Pollutants Emission Inventory Section of the California Air Resources Board (1993) provided us with estimates of emissions of the toxics shown here from the largest emitters in each of the SICs shown here. (The largest emitters were those that emitted more than 25 tons per year of criteria pollutants VOCs, CO, NO_x, SO_x, or PM, or else were on the toxics emissions inventory list of an air-quality management district.)

SIC = Standard Industrial Classification of the U.S. Department of Commerce; n.e.c. = not elsewhere classified.

TABLE 31. GREENHOUSE-GAS EMISSION FACTORS, GRAMS CO_2-EQUIVALENT EMISSIONS FROM FUEL PRODUCTION AND TRANSPORT, PER MILLION BTU OF ENERGY DELIVERED TO END USERS (EXCEPT AS NOTED)

Coal	6,341
Reformulated gasoline	22,802
Conventional gasoline	20,338
Low-sulfur diesel	14,756
Residual fuel oil	13,828
Refinery gas	5,497
Petroleum coke	8,116
Natural gas for heat, CNG[a]	9,509
Nuclear power[b]	13,151
Methanol from natural gas	35,884
Methanol from coal	122,708
Methanol from wood	21,994
Ethanol from corn	118,548
Ethanol from wood[c]	(924)
Synthetic natural gas from wood	14,170
Hydrogen from solar power	100
LPG from a mix of NG and oil[d]	9,992
LPG from natural-gas liquids	7,824
LPG from petroleum	13,439
Wood for power production	5,521

Source: updated version of model documented in DeLuchi (1991, 1993).

[a] Emissions from the generation of electricity used to compress natural gas are calculated separately (as emissions from activities at service stations) and included in the final totals.

[b] Units are grams of CO_2 equivalents per million BTU of power generated.

[c] Negative value is due to emissions credit from the sale of excess power generated by burning portions of feedstock not converted to fuel.

[d] U.S.-average weighted mix of LPG from natural gas and LPG from petroleum.

TABLE 32. ENERGY USE BY REFINERIES IN CALIFORNIA AND NATIONALLY

	California 1991[a]		**USA 1991**[b]		**Calif. 2000**[c]
	Units	*Energy %*	*Units*	*Energy %*	*Energy %*
Crude oil (10^3 barrels)	0	0.00	0	0.00	0.00
Diesel fuel (10^3 barrels)	59	0.07	445	0.09	0.00
Residual oil (10^3 barrels)	413	0.56	10597	2.31	0.40
LPG (10^3 barrels)	4380	3.64	8105	1.09	3.00
Natural gas (10^3 cubic feet)	79360	17.61	698875	25.04	25.00
Refinery gas (10^3 barrels)	42308	54.60	230987	48.15	49.00
Marketable coke (10^3 barrels)	1810	2.35	3113	0.65	2.00
Petroleum coke (10^3 barrels)	10318	13.37	77503	16.22	13.00
Coal (10^3 short tons)	0	0.00	150	0.11	0.10
Electricity (10^6) kWh	5278	3.87	32858	3.89	4.00
Steam (10^6) pounds	13502	3.49	46476	1.94	3.50
H_2 (10^3 cubic feet)	0	0.00	24	0.00	0.00
Oils and other (10^3 barrels)	355	0.44	2474	0.50	0.00
Total process energy (10^{15} BTU)	**0.46**	**100.00**	**2.88**	**100.00**	**100.00**
Process energy/product energy[d]	**0.112**		**0.096**		**0.094**

[a] From unpublished state-level data provided by the EIA's Petroleum Supply Division (EIA, 1993).

[b] EIA, *Petroleum Supply Annual 1991* (1992).

[c] Our assumption, on the basis of the data in this Table and in DeLuchi (1993).

[d] Equal to the total amount of process energy (previous line) divided by the energy content of all of the products of the refinery.

TABLE 33. REFINERY RECEIPTS OF CRUDE OIL BY METHOD OF TRANSPORT, CALIFORNIA AND U.S., 1991

	USA[a]		**California**[b]	
	10^3 barrels	*Percent*	*10^3 barrels*	*Percent*
Pipeline				
Domestic	1,937,272	39%	283,010	41%
Foreign	803,511	16%	0	0%
Tanker				
Domestic	625,023	13%	348,407	51%
Foreign	1,369,021	28%	28,386	4%
Barge				
Domestic	111,900	2%	4,227	1%
Foreign	37,162	1%	1,230	0%
Tank cars				
Domestic	19,047	0%	11,799	2%
Foreign	0	0%	0	0%
Trucks				
Domestic	67,198	1%	7,536	1%
Foreign	0	0%	0	0%
Total				
Domestic	2,760,440	56%	654,979	96%
Foreign	2,209,694	44%	29,616	4%
Grand total	**4,970,134**	**100%**	**684,595**	**100%**

[a] EIA, *Petroleum Supply Annual 1991* (1992).

[b] From unpublished state-level data provided by the EIA's Petroleum Supply Division (EIA, 1993).

TABLE 34. GLOBAL WARMING POTENTIALS (GWPS) OF NON-CO_2 GREENHOUSE GASES, 100-YEAR TIME HORIZON

CH_4	N_2O	CO	NMHC	NO_2
21	270	2	5[a]	4[b]

Source: Delucchi (1995d), on the basis of analyses by Intergovernmental Panel on Climate Change (1992), Martin and Michaelis (1992), and other sources.

[a] Our GWP for NMHCs applies to the carbon mass of the NMHCs, not to the total mass of the NMHCs.

[b] This is the sum of a GWP of 2 due to ozone production (as estimated by Martin and Michaelis, 1992), and a GWP of 2 due to N_2O emissions from deposition of atmospheric nitrogen. The latter is our own estimate (see Delucchi, 1995d, for details).

TABLE 35. FRACTIONAL DISTRIBUTION OF MODES OF ACCESS TO BUS OR RAIL TRANSIT: GREATER SAN FRANCISCO BAY AREA (METROPOLITAN TRANSPORTATION COMMISSION REGION)

	Line-haul transit					
Mode of access to transit	*Local bus*	*Intercity bus*	*School bus*	*Light rail*	*Heavy rail*[a]	*Comm. rail*[b]
Walk	0.914	0.692	0.912	0.667	0.639	0.700
Drive alone	0.037	0.154	0.015	0.333	0.111	0.200
Car passenger	0.025	0.154	0.059	0.000	0.083	0.000
Bicycle	0.000	0.000	0.000	0.000	0.000	0.000
Local bus	0.012	0.000	0.000	0.000	0.000	0.000
Intercity bus	0.000	0.000	0.000	0.000	0.000	0.000
School bus	0.012	0.000	0.000	0.000	0.000	0.000
Light rail	0.000	0.000	0.000	0.000	0.000	0.000
Heavy rail[a]	0.000	0.000	0.000	0.000	0.056	0.100
Commuter rail[b]	0.000	0.000	0.000	0.000	0.028	0.000
Dial-a-ride	0.000	0.000	0.000	0.000	0.028	0.000
Other method	0.000	0.000	0.015	0.000	0.056	0.000
Transit trips in survey[c]	**81**	**13**	**68**	**9**	**36**	**10**
All transit/all trips[d]	*0.015*	*0.002*	*0.012*	*0.002*	*0.007*	*0.002*

Source: our analysis of the primary data from the 1991 statewide travel survey conducted by the California Department of Transportation (1993). n.a. = not applicable (no trips reported by that mode).

[a] BART, in the San Francisco Bay Area, was the only heavy-rail system in operation in California at the time of the 1991 survey.

[b] Caltrain, in the San Francisco Bay Area, was the only commuter-rail system in operation in California at the time of the 1991 survey.

[c] This is the actual number of daily trips by transit, *among those surveyed*. We have not scaled the results to represent total trips by transit for the entire population of the whole region. The extremely low number of intercity bus and rail riders in the survey increases the likelihood that the survey is not representative of the population of riders.

[d] The number of daily trips made by transit divided by the total number of daily trips, among those surveyed.

TABLE 36. FRACTIONAL DISTRIBUTION OF MODES OF ACCESS TO BUS OR RAIL TRANSIT: SACRAMENTO AREA (SACRAMENTO AREA COUNCIL OF GOVERNMENTS REGION)

	Line-haul transit					
Mode of access to transit	*Local bus*	*Intercity bus*	*School bus*	*Light rail*	*Heavy rail*[a]	*Comm. rail*[b]
Walk	0.818	0.917	0.793	0.864	n.a.	n.a.
Drive alone	0.000	0.000	0.027	0.000	n.a.	n.a.
Car passenger	0.159	0.083	0.180	0.000	n.a.	n.a.
Bicycle	0.000	0.000	0.000	0.000	n.a.	n.a.
Local bus	0.000	0.000	0.000	0.091	n.a.	n.a.
Intercity bus	0.000	0.000	0.000	0.000	n.a.	n.a.
School bus	0.000	0.000	0.000	0.000	n.a.	n.a.
Light rail	0.000	0.000	0.000	0.000	n.a.	n.a.
Heavy rail[a]	0.000	0.000	0.000	0.000	n.a.	n.a.
Commuter rail[b]	0.000	0.000	0.000	0.000	n.a.	n.a.
Dial-a-ride	0.000	0.000	0.000	0.000	n.a.	n.a.
Other method	0.023	0.000	0.000	0.045	n.a.	n.a.
Transit trips in survey[c]	**44**	**12**	**222**	**22**	**0**	**0**
All transit/all trips[d]	*0.004*	*0.001*	*0.022*	*0.002*	*0.000*	*0.000*

Source: our analysis of the primary data from the 1991 statewide travel survey conducted by the California Department of Transportation (1993). n.a. = not applicable (no trips reported by that mode).

[a] BART, in the San Francisco Bay Area, was the only heavy-rail system in operation in California at the time of the 1991 survey.

[b] Caltrain, in the San Francisco Bay Area, was the only commuter-rail system in operation in California at the time of the 1991 survey.

[c] This is the actual number of daily trips by transit, *among those surveyed*. We have not scaled the results to represent total trips by transit for the entire population of the whole region. The extremely low number of intercity bus and light-rail riders in the survey increases the likelihood that the survey is not representative of the population of riders.

[d] The number of daily trips made by transit divided by the total number of daily trips, among those surveyed.

TABLE 37. FRACTIONAL DISTRIBUTION OF MODES OF ACCESS TO BUS OR RAIL TRANSIT: LOS ANGELES AREA (SOUTHERN CALIFORNIA ASSOCIATION OF GOVERNMENTS REGION)

Mode of access to transit	**Line-haul transit**					
	Local bus	*Intercity bus*	*School bus*	*Light rail*	*Heavy rail*[a]	*Comm. rail*[b]
Walk	0.819	0.857	0.860	0.667	n.a.	n.a.
Drive alone	0.067	0.020	0.017	0.167	n.a.	n.a.
Car passenger	0.022	0.041	0.118	0.000	n.a.	n.a.
Bicycle	0.008	0.000	0.000	0.000	n.a.	n.a.
Local bus	0.081	0.041	0.004	0.167	n.a.	n.a.
Intercity bus	0.000	0.041	0.000	0.000	n.a.	n.a.
School bus	0.000	0.000	0.000	0.000	n.a.	n.a.
Light rail	0.000	0.000	0.000	0.000	n.a.	n.a.
Heavy rail[a]	0.000	0.000	0.000	0.000	n.a.	n.a.
Commuter rail[b]	0.000	0.000	0.000	0.000	n.a.	n.a.
Dial-a-ride	0.000	0.000	0.000	0.000	n.a.	n.a.
Other method	0.003	0.000	0.000	0.000	n.a.	n.a.
Transit trips in survey[c]	**360**	**49**	**229**	**6**	**0**	**0**
All transit/all trips[d]	*0.013*	*0.002*	*0.008*	*0.000*	*0.000*	*0.000*

Source: our analysis of the primary data from the 1991 statewide travel survey conducted by the California Department of Transportation (1993). n.a. = not applicable (no trips reported by that mode).

[a] BART, in the San Francisco Bay Area, was the only heavy-rail system in operation in California at the time of the 1991 survey.

[b] Caltrain, in the San Francisco Bay Area, was the only commuter-rail system in operation in California at the time of the 1991 survey.

[c] This is the actual number of daily trips by transit, *among those surveyed*. We have not scaled the results to represent total trips by transit for the entire population of the whole region. The extremely low number light rail passengers in the survey increases the likelihood that the survey is not representative of the total population of light-rail users.

[d] The number of daily trips made by transit divided by the total number of daily trips, among those surveyed.

TABLE 38. FRACTIONAL DISTRIBUTION OF MODES OF ACCESS TO BUS OR RAIL TRANSIT: SAN DIEGO AREA

	Line-haul transit					
Mode of access to transit	*Local bus*	*Intercity bus*	*School bus*	*Light rail*	*Heavy rail*[a]	*Comm. rail*[b]
Walk	0.678	1.000	0.837	0.313	n.a.	n.a.
Drive alone	0.017	0.000	0.034	0.250	n.a.	n.a.
Car passenger	0.169	0.000	0.124	0.000	n.a.	n.a.
Bicycle	0.000	0.000	0.006	0.000	n.a.	n.a.
Local bus	0.085	0.000	0.000	0.250	n.a.	n.a.
Intercity bus	0.000	0.000	0.000	0.000	n.a.	n.a.
School bus	0.000	0.000	0.000	0.000	n.a.	n.a.
Light rail	0.017	0.000	0.000	0.125	n.a.	n.a.
Heavy rail[a]	0.000	0.000	0.000	0.000	n.a.	n.a.
Commuter rail[b]	0.000	0.000	0.000	0.000	n.a.	n.a.
Dial-a-ride	0.017	0.000	0.000	0.000	n.a.	n.a.
Other method	0.017	0.000	0.000	0.063	n.a.	n.a.
Transit trips in survey[c]	**59**	**6**	**178**	**16**	**0**	**0**
All transit/all trips[d]	*0.009*	*0.001*	*0.028*	*0.002*	*0.000*	*0.000*

Source: our analysis of the primary data from the 1991 statewide travel survey conducted by the California Department of Transportation (1993). n.a. = not applicable (no trips reported by that mode).

[a] BART, in the San Francisco Bay Area, was the only heavy-rail system in operation in California at the time of the 1991 survey.

[b] Caltrain, in the San Francisco Bay Area, was the only commuter-rail system in operation in California at the time of the 1991 survey.

[c] This is the actual number of daily trips by transit, *among those surveyed*. We have not scaled the results to represent total trips by transit for the entire population of the whole region. The extremely low number of intercity bus and light-rail riders in the survey increases the likelihood that the survey is not representative of the population of riders.

[d] The number of daily trips made by transit divided by the total number of daily trips, among those surveyed.

TABLE 39. FRACTIONAL DISTRIBUTION OF MODES OF ACCESS TO BUS OR RAIL TRANSIT: SAN FRANCISCO BAY AREA, SACRAMENTO AREA, LOS ANGELES AREA, SAN DIEGO AREA

Mode of access to transit	**Line-haul transit**					
	Local bus	*Intercity bus*	*School bus*	*Light rail*	*Heavy rail*[a]	*Comm. rail*[b]
Walk	0.818	0.850	0.838	0.642	0.639	0.700
Drive alone	0.051	0.038	0.024	0.151	0.111	0.200
Car passenger	0.050	0.063	0.133	0.000	0.083	0.000
Bicycle	0.006	0.000	0.001	0.000	0.000	0.000
Local bus	0.064	0.025	0.001	0.132	0.000	0.000
Intercity bus	0.000	0.025	0.000	0.000	0.000	0.000
School bus	0.002	0.000	0.000	0.000	0.000	0.000
Light rail	0.002	0.000	0.000	0.038	0.000	0.000
Heavy rail[a]	0.000	0.000	0.000	0.000	0.056	0.100
Commuter rail[b]	0.000	0.000	0.000	0.000	0.028	0.000
Dial-a-ride	0.002	0.000	0.000	0.000	0.028	0.000
Other method	0.006	0.000	0.001	0.038	0.056	0.000
Transit trips in survey[c]	**544**	**80**	**697**	**53**	**36**	**10**
All transit/all trips[d]	*0.011*	*0.002*	*0.014*	*0.001*	*0.001*	*0.000*

Source: our analysis of the primary data from the 1991 statewide travel survey conducted by the California Department of Transportation (1993). n.a. = not applicable (no trips reported by that mode).

[a] BART, in the San Francisco Bay Area, was the only heavy-rail system in operation in California at the time of the 1991 survey.

[b] Caltrain, in the San Francisco Bay Area, was the only commuter-rail system in operation in California at the time of the 1991 survey.

[c] This is the actual number of daily trips by transit, *among those surveyed*. We have not scaled the results to represent total trips by transit for the entire population of the whole region.

[d] The number of daily trips made by transit divided by the total number of daily trips, among those surveyed.

TABLE 40. SUMMARY OF SURVEYS OF MODES OF ACCESS TO TRANSIT

System	Year	**Mode of access (fractional shares)**				
		Drive car	*Car pass.*	*Walk*	*Feed Bus*	*Other*
Rapid Rail Transit						
Atlanta (WMATA)[a]	1980	0.125	0.076	0.275	0.515	0.009
Boston (MBTA)[a]	1978	0.066	0.036	0.642	0.231	0.025
San Francisco (BART)[a]	1976	0.276	0.206	0.302	0.201	0.015
San Francisco (BART)[b]	1973	0.350	0.240	0.240	0.140	0.030
Washington (WMATA)[a]	1984	0.175	0.123	0.319	0.336	0.047
Chicago (Orange line)[c]	1994	0.130[d]	0.113	0.261	0.407	0.089
Generic old heavy rail[e]	ca. 1977	0.400		0.400	0.200	0.000
Generic new heavy rail[e]	ca. 1977	0.700		0.200	0.100	0.000
Commuter Rail						
Philadelphia (Lindenwold line)[b]	1970	0.670[d]	0.230	0.050	0.050	0.000
Los Angeles (Metrolink)[f]	1994	0.674	0.250[g]	0.003	0.073	0.00
Generic commuter rail[e]	ca. 1977	0.800		0.150	0.050	0.000
Toronto GO-rail[h]	1987	0.725		n.e.	0.275	
Light rail						
San Diego Trolley[a]	1983	0.138	0.079	0.582	0.196	0.005
Generic light rail[e]	ca. 1977	0.300		0.500	0.200	0.000
Bus						
San Bernadino Busway[b]	1974	0.550[d]	0.170	0.230	0.050	0.000
Shirley Busway (Wash. D. C.)[b]	1973	0.240[d]	0.090	0.670	0.000	0.000
Generic express bus[e]	ca. 1977	0.250	n.e.	0.750	0.000	0.000

n.e. = not estimated.

[a] From Charles River Associates (1988). The original source is cited as “reports from individual study areas”. The results for Boston (MBTA) are based on surveys from 6:00 AM to midnight; the results for San Francisco (BART) are based on surveys from 6:00 AM to 3:00 PM, and the results for Washington (WMATA) are based on surveys from 6:30 AM to 9:30 am. “Car passenger” column includes carpool and kiss-and-ride.

[b] From Curry (1976). The data for San Francisco (BART) are from the BART Office of Research; the results for Philadelphia (Lindenwold Line) are from onboard surveys; the results for the San Bernadino Busway are from an onboard survey; and the results for the Shirley Busway are from an onboard survey during the morning peak period.

[c] From a survey of riders in March , 1994 (LaBelle and Stuart, 1995). The Orange line, which opened October 31, 1993, runs around the Chicago Loop and then 11.75 miles out to Midway Airport.

[d] Park and ride.

[e] "Middle estimates" from the Congressional Budget Office (1977). The CBO also provides estimates of modes of access to BART, the Shirley Busway, and the South Shore Extension of the Boston rail system.

[f] From a survey of 288 passengers on the Metrolink's Riverside, California line on November 16, 1994 (Barth et al., 1996).

[g] Barth et al. (1996) reported that 15% of the rail passengers had been dropped off at the station, and that 10% had carpooled.

[h] From the 1987 survey of riders of the commuter rail system of the Greater Toronto Area (Fan et al., 1993). Fan et al. (1993) report access by "auto" and by "transit," with no further disaggregation.

TABLE 41. CBO (1977) ESTIMATE OF CIRCUITY OF TRANSIT TRIPS, AND FRACTION OF TRIP DEVOTED TO TRANSIT

Line-haul mode	Percent of trip devoted to access	Circuity relative to automobile trip
Automobile	0	1.0
Carpool	0	1.15
Vanpool	0	1.20
Dial-a-ride	0	1.40
Old heavy rail	15	1.20
New heavy rail[a]	18	1.30
Commuter rail[b]	18	1.30
Light rail	10	1.20
Express bus	10	1.10

Source: Congressional Budget Office (1977). The access modes are not specified here.

[a] LaBelle and Stuart (1995) surveyed riders of the Chicago rapid-rail “Orange” line in March 1994 and found that the average length of access by auto was 4.0 miles. The average line-haul distance appears to have been around 9 miles. The average distance of the door-to-door drive was 11.3 miles. These results indicate that for access by auto, about 30% of the total trip mileage was access, and the circuity relative to driving door-to-door was 1.15. The access percentage and the circuity estimated for all modes of access (bus, walk, car) would be lower.

[b] A survey of passengers on the Riverside Metrolink commuter rail in Los Angeles appears to support this estimate of the fraction of the trip devoted to access (Barth et al., 1996). Most of the rail passengers drove from home to the station, an average of 13 miles. It appears that the whole trip was on the order of 65 miles, of which then about 20% was access. However, the data of Barth et al. (1996) suggest that the circuity is less than 1.30.

TABLE 42. OUR ASSUMPTIONS: LENGTH OF ACCESS TRIPS TO TRANSIT, AND OF CARPOOL AND VANPOOL TRIPS, RELATIVE TO LENGTH OF BASELINE DIRECT SINGLE-PASSENGER-AUTO TRIP

mode	*Sacramento*	*San Francisco*	*Los Angeles*	*San Diego*	*Boston*	*Wash. D. C.*
Carpool	1.10	1.10	1.10	1.10	1.10	1.10
Vanpool	1.15	1.15	1.15	1.15	1.15	1.15
Bus						
Line haul	1.05	1.05	1.05	1.05	1.05	1.05
access by auto	0.15	0.15	0.15	0.15	0.15	0.15
access by car or vanpool	use access by auto multiplied by carpool or vanpool ratio above					
access by walk or other	0.04	0.04	0.04	0.04	0.04	0.04
LRT						
Line haul	1.00	1.00	1.00	1.00	1.00	1.00
access by auto	0.20	0.20	0.20	0.20	0.20	0.20
access by car or vanpool	use access by auto multiplied by carpool or vanpool ratio above					
access by bus	0.20	0.20	0.20	0.20	0.20	0.20
access by walk or other	0.05	0.05	0.05	0.05	0.05	0.05
HRT						
Line haul	1.00	1.00	1.00	1.00	1.00	1.00
access by auto	0.25	0.25	0.25	0.25	0.25	0.25
access by car or vanpool	use access by auto multiplied by carpool or vanpool ratio above					
access by bus	0.25	0.25	0.25	0.25	0.25	0.25
access by LRT	0.30	0.30	0.30	0.30	0.30	0.30
access by walk or other	0.05	0.05	0.05	0.05	0.05	0.05

Source: Table 41 and our estimates. LRT = light-rail transit, HRT = heavy-rail transit.

TABLE 43. OUR ASSUMPTIONS: DISTRIBUTION OF MODES OF ACCESS TO TRANSIT

mode	*Sacramento*	*San Francisco*	*Los Angeles*	*San Diego*	*Boston*	*Wash. D. C.*
Bus						
Line haul	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
access by car or van	0.10	0.10	0.10	0.10	0.10	0.10
access by walk or other	0.90	0.90	0.90	0.90	0.90	0.90
LRT						
Line haul	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
access by car or van	0.15	0.15	0.15	0.15	0.15	0.15
access by bus	0.15	0.15	0.15	0.15	0.15	0.15
access by walk or other	0.70	0.70	0.70	0.70	0.70	0.70
HRT						
Line haul	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
access by car or van	0.25	0.25	0.25	0.25	0.25	0.25
access by bus	0.05	0.05	0.05	0.05	0.05	0.05
access by LRT	0.02	0.02	0.02	0.02	0.02	0.02
access by walk or other	0.68	0.68	0.68	0.68	0.68	0.68

Source: Tables 39 and 40, and our estimates. LRT = light-rail transit, HRT = heavy-rail transit.

TABLE 44. INPUT "BASE-CASE" PARAMETERS FOR MOTOR VEHICLES USED IN DIRECT DOOR-TO-DOOR TRIP AND TO ACCESS BUSES AND TRAINS.

	Sacramento		**San Francisco**		**Los Angeles**	
	Direct	*Access*	*Direct*	*Access*	*Direct*	*Access*
Fuel for cars	gasoline	LPG	EV	EV	EtOH	EV
Fuel for buses	CNG	CNG	diesel	diesel	MeOH	MeOH
Car or van	car	van	car	van	car	van
Transit mode	n.a.	LRT	n.a.	HRT	n.a.	bus
Carpool or vanpool?	no	no	yes	yes	yes	no

	San Diego		**Boston**		**Washington, D. C.**	
	Direct	*Access*	*Direct*	*Direct*	*Access*	*Direct*
Fuel for cars	CNG	MeOH	gasoline	CNG	MeOH	gasoline
Fuel for buses	CNG	CNG	diesel	CNG	CNG	diesel
Car or van	car	van	car	car	van	car
Transit mode	n.a.	LRT	n.a.	n.a.	LRT	n.a.
Carpool or vanpool?	no	no	yes	no	no	yes

CNG = compressed natural gas; LPG = liquefied petroleum gas; EV = electric vehicle; EtOH = ethanol; MeOH = methanol; LRT = light-rail transit; HRT = heavy-rail transit; n.a. = not applicable.

The base-case is just a scenario, not a prediction of fuels, modes, vehicle occupancy or anything else in a particular region. We examine many other scenarios.

TABLE 45. PERCENTAGE CHANGE IN EMISSIONS PER PASSENGER TRIP, FULL TRIPS INVOLVING TRANSIT VERSUS DOOR-TO-DOOR TRIP BY MOTOR VEHICLES

	Sacramento	San Francisco	Los Angeles	San Diego	Boston	Washington D. C.
NMHC	-97.5%	301.3%	-44.4%	-7.2%	90.2%	-51.6%
CO	-91.3%	87.3%	48.6%	-83.7%	27.9%	-95.2%
NO_x	-70.5%	39.9%	148.4%	-71.2%	793.0%	95.2%
SO_x	84.7%	-5.4%	-89.5%	66.0%	251.4%	708.9%
PM_{10}	-91.5%	-93.1%	-12.0%	-92.3%	94.6%	-94.2%
C_6H_6	-99.0%	87.5%	1013.2%	93.1%	29.7%	353.8%
HCHO	-87.9%	111.1%	1845.7%	-67.8%	706.2%	-74.3%
CH_3CHO	-88.4%	4490.4%	-82.5%	-91.4%	660.4%	-94.9%
$CH_2CHCHCH_2$	-98.6%	infinite	375.9%	infinite	1530.6%	infinite
CH_2CH_2	-93.6%	infinite	25.2%	-94.2%	-90.3%	-99.1%
Fuelcycle GHG	-87.5%	19.1%	52.8%	-59.4%	107.3%	27.6%

CNG = compressed natural gas; LPG = liquefied petroleum gas; EV = electric vehicle; LRT = light-rail transit; HRT = heavy-rail transit; n.a. = not applicable; NMHC = nonmethane hydrocarbons; CO = carbon monoxide; NOx = nitrogen oxides; SOx = sulfur oxides; PM_{10} = particulate matter of less than 10 microns; C_6H_6 = benzene; HCHO = formaldehyde; CH_3CHO = acetaldehyde; $CH_2CHCHCH_2$ = 1,3 butadiene; CH_2CH_2 = ethylene (ethene).

Percentage change is calculated as 100*(Tr-Ad) / Ad, where Tr is grams emitted per passenger trip involving transit, and Ad is grams emitted per door-to-door auto trip. A negative percentage change means that transit reduces emissions per passenger trip. If the direct motor-vehicle trip emits zero, then any emissions from transit will be an "infinite" increase.

These results are for the “base-case” parameters presented in tables throughout this report (e.g., Tables 1, 3, 42, 43, 44).

Emissions from fuel production and station and infrastructure operation and maintenance are included. For transit, emissions from access trips are included.

Because we could not find data on emissions of emissions of acetaldehyde, 1,3-butadiene, and ethylene from power plants (Table 22), the percentage changes shown here overstate the benefit of using electric transportation options.

SCENARIO ANALYSES

SEPARATE SPREADSHEET TABLES NOT AVAILABLE IN THIS VERSION