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GREENHOUSE GAS EMISSION IMPACTS OF ELECTRIC VEHICLES UNDER VARYING DRIVING CYCLES IN VARIOUS COUNTRIES AND U.S. CITIES

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ABSTRACT

Past studies have shown that use of electric vehicles (EVs) can reduce greenhouse gas emissions, relative to emissions from gasoline-fueled internal-combustion-engine vehicles. However, those studies have not considered all aspects that determine greenhouse gas emissions from both gasoline vehicles (GVs) and EVs. Aspects often overlooked include variations in vehicle trip characteristics, inclusion of all greenhouse gases, and vehicle total fuel cycle. In this paper, we estimate greenhouse gas emission reductions for EVs, including these important aspects.

We select four U.S. cities (Boston, Chicago, Los Angeles, and Washington, D.C.) and six countries (Australia, France, Japan, Norway, the United Kingdom, and the United States) and analyze greenhouse emission impacts of EVs in each city or country. These selected cities and countries have distinct differences in electric power-plant fuel mixes. We also select six driving cycles developed around the world (i.e., the U.S. federal urban driving cycle, the Economic Community of Europe cycle 15, the Japanese 10-mode cycle, the Los Angeles 92 cycle, the New York City cycle, and the Sydney cycle). Note that we have not analyzed EVs in high-speed driving (e.g., highway driving), where the results would be less favorable to EVs; here, EVs are regarded as urban vehicles only. We choose one specific driving cycle for a given city or country and estimate the energy consumption of four-passenger compact electric and gasoline cars in the given city or country. Thus, the city- or country-specific vehicle energy consumption estimates reflect effects of both vehicle driving cycles and electric power-plant mixes. Finally, we estimate total fuel cycle greenhouse gas emissions of both GVs and EVs by accounting for emissions from primary energy recovery, transportation, and processing; energy product transportation; and power-plant and vehicle operations.

We estimate that EVs reduce greenhouse gas emissions in all selected U.S. cities and countries. In Norway, where hydro-power provides electricity for EVs, and in Chicago, where nuclear power provides electricity for EVs, EVs achieve per-mile greenhouse gas emission reductions of more than 98%. In France and Japan, where large amounts of electricity are generated from nuclear power and other clean power sources, EV emission reductions are 80-90%. Moderate EV emission reductions of 35-60% occur in the U.K., Boston, the U.S., and Los Angeles. Only a small EV emission reduction of about 15% is achieved in Australia and Washington, D.C., where significant amounts of electricity are generated from coal-fired power plants.

INTRODUCTION

The potential global warming caused by anthropogenic greenhouse gases (GHG) has increasingly become a concern worldwide. To limit potential global warming, national and international organizations have proposed to reduce GHG emissions from various sources. Among GHG-emitting sources, the transportation sector is one of the largest contributors. For example, in industrial countries, CO_2 emissions from the transportation sector account for about 30% of total anthropogenic CO_2 emissions (International Energy Agency, 1993a). To control the total amount of GHG emitted to the atmosphere, reducing transportation GHG emissions becomes necessary. Consequently, various measures--such as reductions in vehicle usage and improvements in vehicle fuel efficiency--have been proposed to reduce transportation GHG emissions. Recently, it has been suggested that use of alternative transportation fuels could have significant impacts on transportation GHG emissions. This paper analyzes in detail impacts on GHG emissions of using battery-powered electric vehicles (EVs) only.

In major industrial countries (e.g., the U.S., western Europe, and Japan), EVs have been promoted to replace gasoline-powered internal-combustion-engine vehicles for curbing urban air-pollution problems. In California, vehicle manufacturers will be required, beginning in year 1998, to sell 2% of their new light-duty vehicles as "zero-emission vehicles" (virtually certain to be EVs, with current vehicle technology advances). The EV share requirement increases to 10% in the year 2003. Mainly as a result of California's zero-emission vehicle requirement, the three U.S. vehicle manufacturers and major European and Japanese vehicle manufacturers have produced some prototype EV models, and major studies are currently being conducted to explore the potential EV market.

Use of EVs to replace gasoline vehicles (GVs) has significant implications for transportation GHG emissions. EV GHG emission impacts are determined by the energy efficiencies of both GVs and EVs and by the types of power plants to be used for EV recharging. Because of these factors, EV GHG emission impacts can vary in different regions. GHG emissions are produced during up stream fuel processes, as well as during vehicle operation. In this paper, we estimate GHG emission changes with use of EVs by considering vehicle efficiency differences for various driving cycles, electric generation mixes in different countries and U.S. cities, and emissions from various stages of the fuel cycle, from primary energy recovery to vehicle operation.

PREVIOUS STUDIES

DeLuchi (1991 and 1993) has performed a detailed, comprehensive study of estimating GHG emissions for various transportation fuels. He identifies the stages of various fuel processes, from primary energy recovery to vehicle operation, and estimates the amount of energy consumed and the types of energy sources consumed for each identified energy stage. He develops GHG emission factors for various energy combustion processes and estimates total fuel cycle GHG emission changes with the use of various transportation fuels (i.e., reformulated gasoline, diesel, methanol, natural gas [NG], ethanol, hydrogen, and electricity). For scenarios having different energy efficiencies and power-plant electric generation mixes, he demonstrates that EV GHG emission impacts could vary significantly with different assumptions about vehicle efficiencies and power-plant mixes. In estimating vehicle energy consumption, he implicitly uses the U.S. federal urban driving schedule. The impacts of driving cycles on vehicle energy consumption are not explicitly analyzed. By selecting the urban driving cycle instead of the combined urban and highway cycle (the latter is commonly used for evaluating vehicle fuel economy), DeLuchi chooses to assume that EVs are urban vehicles only and shows their merits for that use.

Relying on DeLuchi's study, the International Energy Agency (IEA) has recently completed a study to compare fuel cycle GHG emissions of various alternative-fuel vehicles

(International Energy Agency, 1993a). The IEA estimates EV GHG emission changes for different primary energy sources (e.g., coal, NG, and nuclear power). Because of different assumptions about energy efficiencies, the IEA study shows large increases or decreases in EV GHG emissions. The IEA study neither estimates country-specific EV GHG emission changes nor addresses impacts of different driving cycles on vehicle energy efficiencies.

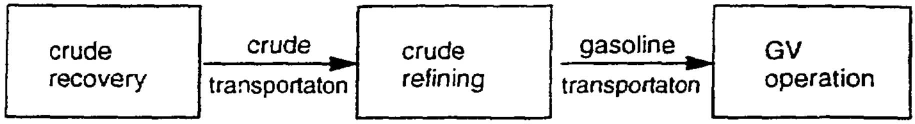
A recently completed U.S. Department of Energy study estimates emission changes associated with EV use in various U.S. regions (U.S. Department of Energy, 1993). Besides emissions of criteria pollutants, the study analyzes EV impacts on CO_2 emissions. The study concludes that CO_2 emissions could be increased or decreased with assumptions about different power-plant mix for EV recharge. The study includes neither greenhouse gases other than CO_2 nor emissions from up stream fuel production processes except power-plant operations. When estimating EV electricity consumption, the study explicitly assumes the U.S. federal urban driving cycle. The study does not address the impacts of various driving cycles on vehicle energy efficiencies.

Wang and Santini (1993) analyze EV emission changes for both criteria pollutants and CO_2 in four U.S. cities (Chicago, Denver, Los Angeles, and New York) under varying driving cycles. They find that, in a given city, driving cycles can have significant impacts on EV emission changes by changing GV fuel economy and EV electricity consumption. They find that the electric power-plant mix for EV recharge is the most significant factor in determining the differences in EV emission changes among the studied cities. The study includes power-plant emissions and refinery-plant emissions, but not emissions from other up-stream activities. The study does not include greenhouse gases other than CO_2.

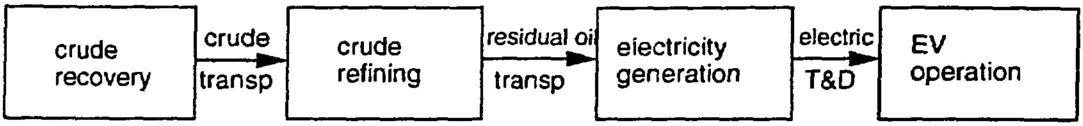
ANALYTIC APPROACH

We analyze GHG emissions of GVs and EVs on a total fuel cycle basis. That is, GHG emissions from primary energy recovery, transportation, and processing; energy product transportation; and power-plant and vehicle operation are included. Figure 1 shows total fuel cycles for GVs and EVs. For EVs, four fuel cycles are included--crude oil to EV operation, coal to EV operation, NG to EV operation, and uranium to EV operation. Electricity is also generated from such other sources as hydro-power, solar energy, and wind, but GHG emissions from these fuel cycles are minimal. We simply treat GHG emissions from these fuel cycles as being zero.

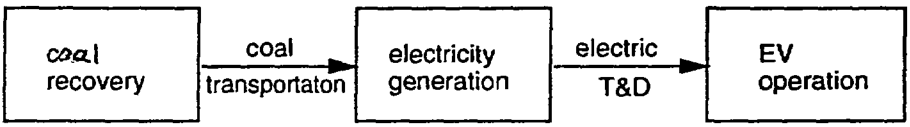
Total fuel cycle GHG emissions of GVs and EVs are calculated in grams per mile. To do this, we estimate per-mile energy consumption of GV and EV operation with a computer model. We estimate the energy consumption of producing the estimated per-mile energy consumption for vehicle operation during various energy stages (i.e., primary energy production, transportation, and processing; energy product transportation; and electricity generation). For a specific fuel cycle, we estimate GHG emissions attributable to energy consumption during each energy conversion stage. We add the GHG emissions of each stage together to obtain the total fuel cycle emissions for the cycle. Besides GHG emissions from energy consumption, we include GHG emissions due to fuel leaks. Per-mile GHG emission changes due to EV use are calculated by comparing GHG emissions from EVs with those from GVs.



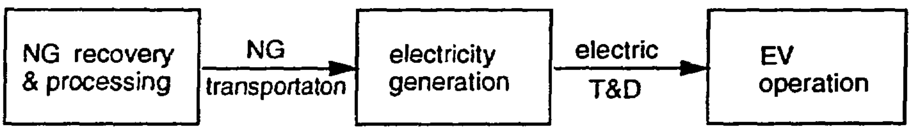
(a) Crude to GV Operation



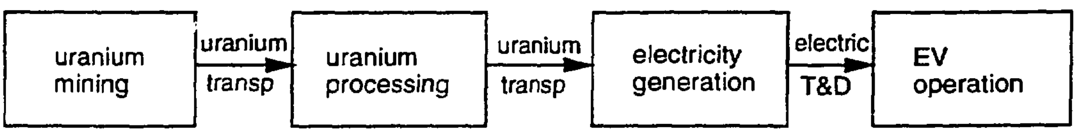
(b) Crude to EV Operation



(c) Coal to EV Operation



(d) NG to EV Operation



(e) Uranium to EV Operation

Figure 1. Fuel Cycles of GVs and EVs

We include three greenhouse gases--carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). Total GHG emissions are calculated by adding global warming potential-adjusted emissions of these three gases together. GV and EV fuel cycles also produce other greenhouse gases, such as carbon monoxide, nitrogen oxide, and volatile organic gases. Per-mile emissions and global warming potentials of these gases are generally small, so they are ignored in the estimation.

To analyze EV GHG impacts of a variety of electric power-plant mixes, we include four U.S. cities (Boston, Chicago, Los Angeles, and Washington, D.C.) and six countries (i.e., Australia, France, Japan, Norway, the United Kingdom, and the United States). These cities and countries have distinctly different electric power-plant mixes. Power-plant mixes for the selected cities and countries are presented in Table 1. About 90% of electricity is generated from oil in Boston. All electricity for EVs is generated from nuclear power in Chicago. 85% of electricity is generated from NG in Los Angeles. 87% of electricity is generated from coal in Washington, D.C. 80% of electricity is generated from coal in Australia. 86% of electricity is generated from nuclear and other clean sources in France. 43% of electricity is generated from nuclear and other clean sources in Japan. Virtually all electricity is generated from hydro-power in Norway. 47% of electricity is generated from coal in the U.K., whereas 49% of electricity is generated from coal in the U.S.; note that the power-plant mix in the U.S. is similar to that in the U.K.

Table 1. Electric Power-Plant Mixes for Studied Cities and Countries (%)

	Coal	Oil	NG	Nuclear	Others[a]	Remarks[b]
Boston	0	89	11	0	0	1988 average mix[c]
Chicago	0	0	0	100	0	2000 marginal mix[d]
Los Angeles	8	0	85	0	7	2000 marginal mix[d]
D.C.	87	12	1	0	0	1988 average mix[c]
Australia	80	2	9	0	9	2000 average mix[e]
France	9	2	3	74	12	2000 average mix[e]
Japan	18	19	20	32	11	2000 average mix[e]
Norway	1	0	0	0	99	2000 average mix[e]
U.K.	47	11	22	17	3	2000 average mix[e]
U.S.	49	4	17	18	12	2000 average mix[e]

[a] Others include hydro-power, wind, solar energy, and other renewable sources. They are assigned zero GHG emissions.
[b] Average mix is the power-plant mix for a utility system. Marginal mix is the calculated power-plant mix for EV recharge. To be precise, marginal mixes should be used here for calculating EV GHG emissions. However, marginal mixes for two U.S. cities and six countries are not available. Thus, average mixes are adopted for these cities and countries.
[c] From DeLuchi (1993).
[d] From Wang and Santini (1993).
[e] From the International Energy Agency (1993b).

The six driving cycles (with different characteristics) selected are Economic Community of Europe cycle 15 (ECE-15), U.S. federal urban driving schedule (FUDS), Japanese 10-mode cycle (Japan-10), Los Angeles 92 cycle (LA-92), New York City cycle (NYCC), and Sydney cycle. The ECE-15 is used for emission testing in the Economic Community of Europe. The FUDS is used in the U.S. and Australia for emission testing. The Japan-10 is used in Japan for emission testing. The LA-92 was developed in 1992 based on driving patterns in Los Angeles. The NYCC was developed to reflect slow traffic in downtown New York. The Sydney cycle was developed to reflect driving patterns in Sydney, Australia. Specifications of these driving cycles are presented in Table 2 below. Energy consumption of GVs and EVs under each driving cycle is estimated with a computer model developed at Argonne National Laboratory. In comparing GHG emissions between GVs and EVs, we choose for a given city or country the driving cycle developed or used in the city or country. That is, we choose the ECE-15 for the three European countries (France, Norway, and the U.K.); the FUDS for the U.S., Chicago, and Washington, D.C.; the Japan-10 for Japan; the LA-92 for Los Angeles; the NYCC for Boston; and the Sydney for Australia.

Table 2. Specifications of Driving Cycles Used in the Study

Driving Cycle	Duration, s	Avg. Speed, mph	Top Speed, mph	Idling, %
ECE-15[a]	4x195	11.7	31.1	29.2
FUDS[b]	1371	19.6	56.7	19.0
Japan-10[a]	5x135	10.6	24.9	25.9
LA-92[c]	1431	24.7	67.2	16.0
NYCC[d]	600	7.0	26.4	38.6
Sydney[a]	637	20.8	50.3	18.4

[a] From Milkins and Watson (1983).
[b] From Environment Reporter (1992).
[c] From Austin et al. (1992).
[d] From Environment Reporter (1993).

This paper analyzes EV impacts on GHG emissions for the year 2000. Energy efficiencies, power-plant mixes, and vehicle technologies are projected for that year.

GREENHOUSE GAS EMISSION ESTIMATES

This section presents methods and data used in calculating GHG emissions for each of the total fuel cycle stages--primary energy production, transportation, and processing; energy product transportation; electricity generation; electricity transmission and distribution (T&D); and vehicle operations.

Greenhouse Emissions for Primary Energy Production

Crude

GHG emissions from crude oil recovery come from two sources--fossil fuel combustion needed for recovery operations and associated gas vented and flared during recovery. DeLuchi (1991) estimates the amount of fuel needed for recovering crude oil. He notes that crude oil, diesel fuel, residual oil, NG, gasoline, and electricity are used in crude recovery operations. He estimates the shares of these energy products in the amount of fuels burnt for crude recovery. He presents GHG emission factors for fuel combustion in grams per million Btu (mmBtu) fuel input for each identified energy product (DeLuchi, 1993). Using DeLuchi' data on the amount of fuels needed, the shares of various energy products, and GHG emission factors for these energy products, we calculate GHG emissions in grams per mmBtu of crude oil recovered. We use our own estimates of GHG emission factors for electricity in this study (we present electricity GHG emission estimates in a later section).

In estimating GHG emissions from vented and flared associated gas, we use DeLuchi's estimate of the amount of vented and flared associated gas per mmBtu of crude oil recovered and his estimated GHG emission factor for NG combustion.

Natural Gas

During NG recovery and processing in NG fields, GHG emissions are produced from fossil-fuel combustion and NG leaks (resulting in CH_4 emissions). DeLuchi estimates that over 90% of the energy used for NG recovery and processing is obtained from NG. Small amounts of crude oil, diesel fuel, gasoline, and electricity are also used for NG recovery and processing. Using DeLuchi's estimates of energy use for NG recovery and processing, shares of energy products, and GHG emission factors, we calculate GHG emission factors in grams per mmBtu of NG recovered and processed.

We use DeLuchi's estimate of NG leaks during NG recovery and processing, we assume that the leaked NG is CH_4.

Coal

Two sources contribute to GHG emissions from coal mining and preparation--fossil-fuel combustion and CH_4 released during coal mining operations. DeLuchi estimates that diesel fuel and electricity are used primarily for coal mining and preparation. Small amounts of residual oil, NG, coal, and gasoline are also used. With DeLuchi's data, we estimate GHG emission factors in grams per mmBtu of coal mined and prepared.

We adopt DeLuchi's estimated CH_4 release rate of 246 grams per mmBtu of coal mined (DeLuchi, 1993).

Uranium

Diesel fuel, NG, coal, gasoline, and electricity are used for uranium recovery. Using DeLuchi's estimate of energy consumption, the shares of energy products, and GHG emission factors, we calculate GHG emissions in grams per mmBtu of electricity produced from uranium during uranium recovery.

Greenhouse Gas Emissions for Primary Energy Transportation

Crude oil is transported to refining plants by pipelines, ships, trains, and trucks. Consequently, electricity, residual oil, and diesel fuel are consumed during crude oil transportation. NG is transported to electric power plants through pipelines, and NG and electricity are consumed during NG transportation. Coal is transported to electric power plants by ships, trains, and trucks, and residual oil and diesel are consumed during coal transportation. Uranium is transported to uranium-enrichment plants by trucks, and diesel fuel is consumed during uranium transportation.

Using DeLuchi's estimates of energy consumption for transporting each primary energy source, the shares of energy products, and GHG emission factors for energy product combustion, we estimate GHG emission factors in grams per mmBtu of each primary energy source transported. In estimating GHG emissions during NG transportation, we include NG leaks from pipelines.

Greenhouse Gas Emissions for Primary Energy Processing

Among the four primary energy sources, crude oil and uranium need to be intensively processed in crude-refining plants and uranium-enrichment plants, respectively.

Two crude refinery products--gasoline and residual oil--are relevant to this study. Gasoline is used for GV operation. Residual oil is used for electricity generation. In the U.S., reformulated gasoline with low emission characteristics will be required in 2000 (the target year of this study). Thus, we specify that reformulated gasoline is used in the four U.S. cities and the U.S. and that conventional gasoline is used in the three European countries, Australia, and Japan. Reformulated gasoline requires higher refining intensity than conventional gasoline, and conventional gasoline, higher than residual oil. Thus, reformulated gasoline results in the highest GHG emission factors per mmBtu produced, conventional gasoline the second highest, and residual oil the lowest.

Refinery GHG emissions can be categorized as non combustion and combustion GHG emissions. Non combustion emissions include CO_2 emissions from CO conversion and CH_4 and N_2O emissions from various non combustion sources. DeLuchi has estimated non combustion GHG emissions, and we adopt his estimated values here. Combustion emissions include CO_2 emissions from fossil combustion for refinery operations. With DeLuchi's estimate of energy consumption for crude refining, the shares of energy products, and GHG emission factors for energy product combustion, we estimate GHG emissions in grams per mmBtu for reformulated gasoline, conventional gasoline, and residual oil produced.

Uranium enrichment consumes a significant amount of electricity and a small amount of NG. Using DeLuchi's estimate of energy consumption, the shares of electricity and NG, and his estimated GHG emission factors for NG combustion and our estimated GHG emission factors for electricity, we estimate GHG emission factors in grams per mmBtu of electricity produced from uranium.

Greenhouse Emissions for Energy Product Transportation

Three energy products must be transported to use sites--gasoline to service stations, and residual oil and enriched uranium to electric power plants. Gasoline and residual oil are transported by pipelines, ships, trains, and trucks; and electricity, residual oil, and diesel fuel are consumed during gasoline and residual oil transportation. Enriched uranium is transported by trucks. Due to the extremely high energy density of enriched uranium, the energy consumption per mmBtu of uranium transported should be very small. As a result, GHG emissions from transporting enriched uranium are negligible, so we ignore GHG emissions from enriched uranium transportation.

Using DeLuchi's estimates of energy consumption for gasoline and residual oil transportation, the shares of energy products, and his estimated GHG emission factors for energy product combustion, we calculate GHG emission factors in grams per mmBtu of gasoline and residual oil transported.

Greenhouse Emissions for Electricity Generation

Operations of oil-, NG-, and coal-fired electric power plants generate GHG emissions. Nuclear power-plant operations do not produce GHG emissions. DeLuchi estimates GHG emission factors in grams per mmBtu of fuel input for each of the three fossil-fuel power-plant types. To convert DeLuchi's GHG emission factors to GHG emission factors in grams per mmBtu of electricity output, power-plant conversion efficiencies are needed. Table 3 presents power-plant conversion efficiencies for the three power-plant types in each country. Because city-specific efficiency data are lacking, we apply U.S. power-plant conversion efficiencies to the four U.S. cities, as well as to the U.S.

Table 3. Electric Power-Plant Conversion Efficiencies (%)

Country	Coal Plant	Oil Plant	NG Plant	Reference
Australia[a]	33	34	36	DeLuchi (1993)
France	33	30	53	DeLuchi (1993)
Japan	41	42	41	DeLuchi (1993)
Norway[a]	33	n.a.[b]	n.a.[b]	DeLuchi (1993)
U.K.	32	32	26	DeLuchi (1993)
U.S.	35	33	35	Wang and DeLuchi (1992)

[a] No power-plant conversion efficiencies are available for Australia and Norway. We use the ECE-wide (Economic Community of Europe) average efficiencies for these two countries.

[b] Not applicable, because there are no oil- or NG-fired power plants in Norway.

In calculating GHG emissions in grams per mmBtu of electricity available to users at wall outlets, energy losses of electricity T&D need to be considered. We use an electric T&D loss of 8% for the four U.S. cities and for the U.S. (Wang and DeLuchi, 1992) and a loss of 5% for Australia, Japan, and the three European countries (DeLuchi, 1993).

Greenhouse Gas Emissions from Vehicle Operation

GHG emissions, especially CO_2 emissions, are directly related to GV energy consumption. We estimate GV and EV per-mile energy consumption for a specified gasoline car and electric car under each of the six driving cycles selected. Then, we calculate GHG emissions from vehicle operations.

GV and EV Specifications

We assume a generic four-passenger compact car for GVs and EVs in this analysis. Based on advances in electric and gasoline vehicle technologies between now and 2000, we project performance attributes and vehicle specifications for the generic gasoline car and electric car. Table 4 presents the performance attributes and specifications of the assumed gasoline car and electric car.

Table 4. Performance and Specifications of the Assumed Gasoline and Electric Cars

Parameter	Gasoline Car	Electric Car
Curb Weight, lb	3067	2454[a]
Payload, lb	600	600
Drive Train Efficiency, %	85	85
Motor Efficiency, %	na[b]	90
Rolling Resistance	0.008	0.008
Frontal Area, ft^2	28.0	28.0
Drag Coefficient	0.25	0.25
Acc. Time (0-60 mph), s	12	15[c]
Top Speed, mph	118	65[c]
Range, miles	400	120[c]

[a] Not including battery weight, which is calculated separately; assumed to be 80% of curb weight of GV.
[b] Not applied.
[c] At 80% depth-of-discharge (DOD) of battery.

Vehicle Driving Cycles

Vehicle fuel consumption varies significantly with trip characteristics (e.g., average speed, top speed, and idling time). Driving cycles in the form of repeatable speed-time sequences are designed to represent driving patterns in a particular environment. Six driving cycles are selected in this study to represent a variety of driving patterns in different parts of the world. Table 2 shows the specifications of the six driving cycles used. As the table shows, the NYCC, the Japan-10, and the ECE-15 have low average speeds, low top speeds, and long idling time; they represent severely congested urban driving. The LA-92, the FUDS, and the Sydney have high average speeds, high top speeds, and short idling time, representing combinations of urban and freeway driving.

Simulation of Energy Consumption of Gasoline and Electric Vehicles

Fuel consumption of GVs and EVs is estimated by using the EAGLES computer model developed at Argonne National Laboratory. EAGLES is an upgraded, expanded version of DIANE--an interactive computer model for simulating battery performance in EV applications (Marr et al., 1990 and 1992). To simulate GV fuel consumption, a sub-model based on an analytic formulation developed by An and Ross (1993) is incorporated in EAGLES. The analytic formulation is based on an engine map approximation, with the assumption that the rate of fuel consumption is a linear function of engine output power. This is a reasonable approximation, especially for engines running at fixed speed and at power levels less than roughly two-thirds of the power at wide-open throttle. EAGLES has been calibrated with laboratory test data, including EPA test data for several 1991 model-year vehicles.

For a vehicle with specified characteristics and performance attributes, EAGLES calculates the instantaneous road-load power from the force required to overcome the air drag, the rolling resistance, and grade effects while, at the same time, maintaining the vehicle at the specified speed. The power delivered by the engine (or the battery, in the case of an EV) needs to overcome not only the tractive force, but also the losses in drivetrain and vehicle accessories. EAGLES can take into consideration energy recovered from the regenerative braking system applied to EVs.

Estimated GV and EV Energy Consumption

Table 5 shows the results of GV energy consumption for the six driving cycles simulated by EAGLES. The results indicate that the three urban, congested driving cycles experience significantly higher energy consumption than the three urban-freeway combination driving cycles, with the NYCC having the highest energy consumption. The three urban-freeway combination cycles show very similar energy consumption.

Table 5. Estimated Fuel Economy of the Gasoline Vehicle

Driving Cycle	Fuel Economy[a], mile/gal	Energy Consumption[b], Btu/mile
ECE-15	20.0	5750
FUDS	24.8	4637
Japan-10	17.1	6725
LA-92	24.5	4694
NYCC	13.8	8333
Sydney	24.3	4733

[a] Assuming cold-start cycle.
[b] Assuming 115,000 Btu/gal for gasoline.

For the EV case, the capacity and weight of the battery applied to the specified electric car are calculated through an iterative procedure for the FUDS. In determining battery capacity and weight, battery performance corresponding to the USABC (U.S. Advanced Battery Consortium) mid-term goals (Automotive Engineering, 1992) is assumed. The final battery size is determined to be capable of providing adequate power and energy to meet the acceleration rate of 15 seconds to go from 0 to 60 mph (after the battery has been discharged to 80% of its fully charged capacity) and the driving range of about 120 miles. The determined battery size and performance are presented in Table 6. For the FUDS, the ECE-15, Japan-10, and the Sydney driving cycles, the EAGLES simulation reveals that the power requirement for the 15-second acceleration is much more stringent than the energy requirement for the 120-mile range.

Table 6. Battery Characteristics for the Electric Vehicle

Specific Power @ 80% DOD[a], W/kg	150
Specific Energy @ 3-h rate[a], Wh/kg	80
Battery Weight[b,c], lb	1080
Energy Capacity[b], kWh	39.2
Power Capacity[b], kW	73.5

[a] USABC mid-term battery goal.
[b] Determined from EAGLES simulation.
[c] Total EV weight, including EV body and battery, is 3,534 lb. The EV battery accounts for 30% of total EV weight.

EAGLES calculates EV energy consumption with the determined battery weight and assumed EV performance and characteristics. In determining the EV energy requirement, 50% of the kinetic energy available during vehicle braking is assumed to be converted back as useful electric energy in the battery by the regenerative braking system. Overall, regenerative braking energy reduces total EV energy requirements by approximately 20%.

Table 7 shows the per-mile EV energy consumption predicted by EAGLES. The ECE-15 has the lowest energy consumption because a significant amount of energy is estimated to be recoverable by the regenerative braking system. The LA-92 has the highest energy consumption due to an energy penalty of severe power demand (high acceleration rates) through the cycle. In contrast to GVs, the ECE-15 and the Japan-10 have lower per-mile EV energy consumption than the three urban-freeway combination driving cycles, primarily due to regenerative braking energy recovered for EVs. The highest energy consumption for both GVs and EVs occurs under the NYCC; the increase in energy consumption between other cycles and the NYCC is much higher for GVs than for EVs. In summary, the EAGLES simulation shows that EVs have large energy benefits relative to GVs in urban, congested driving cycles.

Table 7. Estimated Electricity Consumption for the Electric Vehicle

Driving Cycle	kWh/mile from battery	kWh/mile at wall outlet[a]	Btu/mile at wall outlet[a]
ECE-15	0.197	0.265	904
FUDS	0.233	0.345	1177
Japan-10	0.213	0.316	1078
LA-92	0.302	0.447	1525
NYCC	0.272	0.403	1375
Sydney	0.256	0.379	1293

[a] Assuming a battery efficiency of 75% and a charger efficiency of 90%.

Per-Mile Greenhouse Gas Emissions

Per-mile CO_2 emissions from GVs are calculated be means of the following equation:

$$CO_2 = (\text{gasoline density x gasoline carbon content/MPG - CO x } 12/28) \text{ x } 44/12$$

Where CO_2 is in grams per mile, MPG is estimated from EAGLES, CO is in grams per mile (assumed to be 10 grams per mile here), gasoline density is assumed to be 2,719 grams per gallon for conventional gasoline and 2,749 grams per gallon for reformulated gasoline, gasoline carbon content is assumed to be 86.6% for conventional gasoline and 83.3% for reformulated gasoline, 12 is carbon molecular weight, 28 is CO molecular weight, and 44 is CO_2 molecular weight.

We assume emission rates of 0.05 grams per mile for CH_4 and 0.06 grams per mile for N_2O. Both rates are from DeLuchi (1993). GHG emissions during EV operations are simply zero.

Total Fuel Cycle Greenhouse Gas Emissions

Since we calculate GHG emissions in grams per mmBtu of energy recovered, transported, or processed, and since direct energy losses during a fuel cycle are negligible, we can directly add GHG emissions from the energy stages of a fuel cycle together to obtain total GHG emissions for the fuel cycle in grams per mmBtu of energy available at gasoline service stations or at electric wall outlets.

There are four fuel cycles for EVs--oil, NG, coal, and uranium. GHG emissions are calculated for each fuel cycle. We use power-plant mix data in Table 1 as weighting factors to calculate utility average total fuel cycle GHG emissions for EVs in each city or country.

Emission factors are calculated for each of the three greenhouse gases--CO_2, CH_4, and

N_2O. Emissions of these three pollutants are weighted with their global warming potentials and added together. We adopt global warming potentials for a 100-year time horizon, as proposed by the Intergovernmental Panel on Climate Change. The potentials are 1 for CO_2, 26 for CH_4, and 270 for N_2O (International Energy Agency, 1993a).

RESULTS

GV Fuel Cycle Greenhouse Emissions

Figure 2 presents per-mile GHG emissions from GVs in the four U.S. cities and in the six countries. Among the five energy stages, GV operation produces the highest GHG emissions, crude refining produces the second highest GHG emissions, crude recovery produces a small amount of GHG emissions, and crude and gasoline transportation produces the smallest amount of GHG emissions.

Across the four U.S. cities and the six countries, GHG emissions from GVs range from 430 to as much as 770 grams per mile. Low emissions occur in the U.S.; Washington, D.C.; Chicago; Los Angeles; and Australia, where GV fuel economy is high (Table 5). The highest GHG emissions occur in Boston, where GV fuel economy is the lowest due to use of the New York City cycle. Japan and the three European countries are estimated to have relatively high GHG emissions due to the relatively low GV fuel economy estimated there. Per-mile GV GHG emissions are inversely correlated with GV fuel economy.

The driving cycle applied to each city or country is the only factor determining the differences in GV fuel economy. Thus, driving cycles are the single most important factor determining GV GHG emissions. Because different driving cycles are applied to different cities or countries, GV GHG emissions almost double from the lowest values in Chicago, Washington, D.C., and the U.S. to the highest values in Boston. It is critically important to choose appropriate driving cycles for target areas in determining GV fuel economy, and thus GV GHG emissions.

Among the three greenhouse gases, CO_2 emissions contribute to over 95% of GV total fuel cycle emissions, global warming potential-adjusted N_2O emissions contribute to about 4%, and global warming potential-adjusted CH_4 emissions contribute to less than 1%.

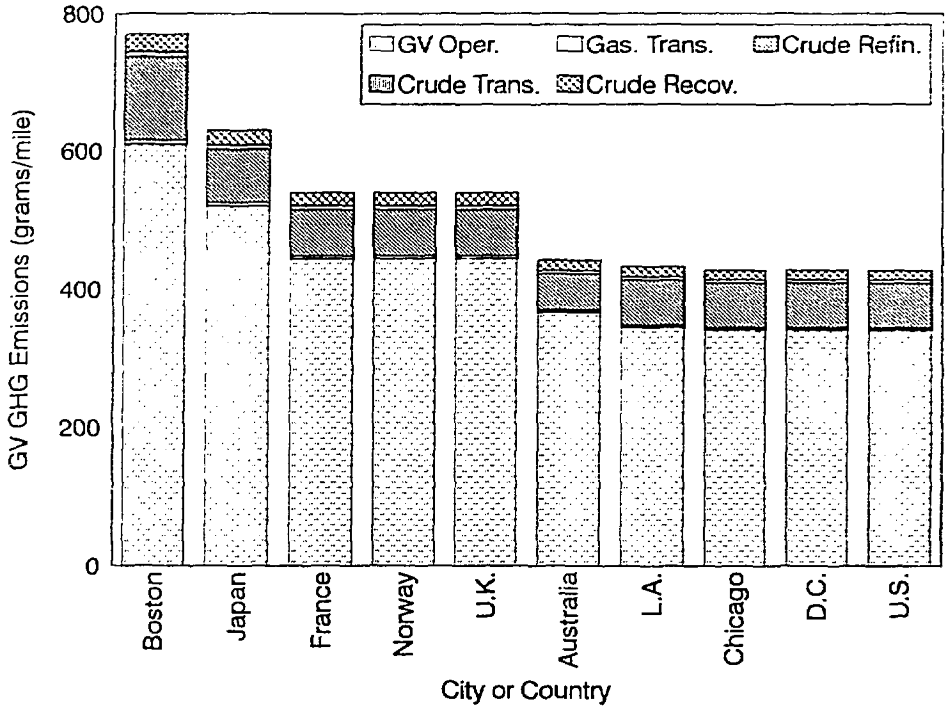


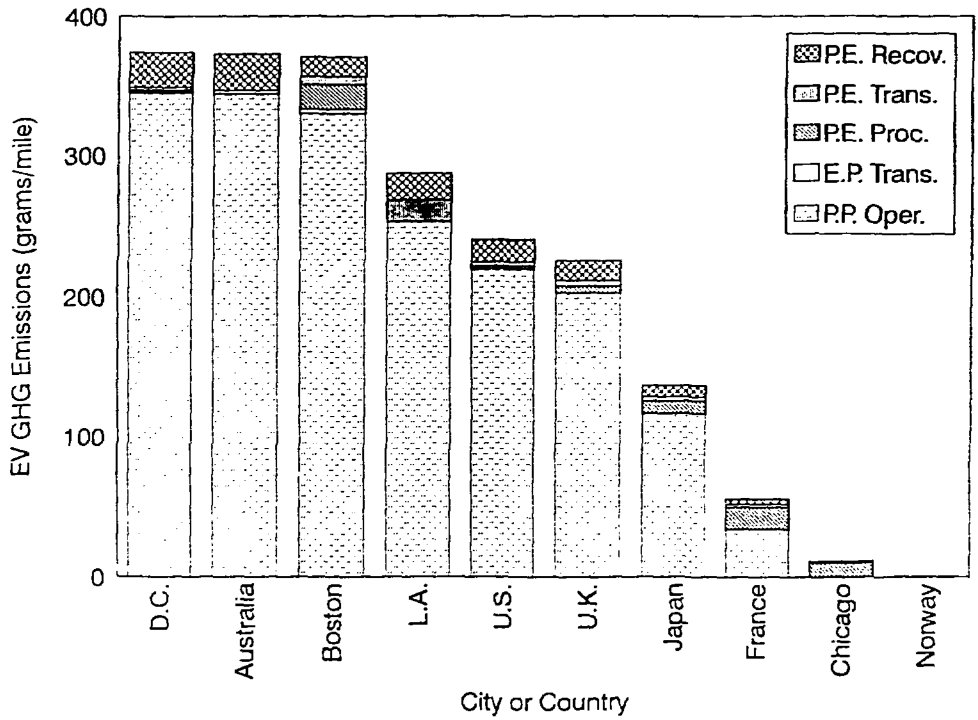
Figure 2. GV Fuel Cycle Greenhouse Gas Emissions

EV Fuel Cycle Greenhouse Gas Emissions

Figure 3 presents EV total fuel cycle GHG emissions in the four U.S. cities and in the six countries. Except in Chicago and Norway, power-plant GHG emissions account for most of the total GHG emissions. Nuclear power plants are projected to generate electricity for EVs in Chicago, and hydro-power, in Norway. Power-plant emissions in both places are zero. In Washington, D.C., Australia, Los Angeles, the U.S., and the U.K., primary energy recovery is the second largest source of GHG emissions. In Washington, D.C., Australia, the U.K., and the U.S., coal-fired power plants generate a significant amount of electricity for EVs. CH_4 emissions from coal mining are the major contributor to primary energy recovery GHG emissions in these cities and countries. In Los Angeles, NG-fired power plants generate a large amount of electricity for EVs. NG recovery and processing are a major source of GHG emissions there. In Boston, France, and Chicago, GHG emissions from primary energy processing (crude refining in Boston and uranium enrichment in Chicago and France) are the second largest source. In Japan, both primary energy recovery and processing are important GHG emission sources. GHG emissions from transportation of primary energy sources and energy products are minimal.

EV fuel cycle GHG emissions range from as little as almost zero in Norway to as much as 380 grams per mile in Washington, D.C. EV GHG emissions in Norway and Chicago are minimal, because hydro-power provides electricity for EVs in Norway and nuclear power does so in Chicago. EV GHG emissions in France and Japan are small because large amounts of electricity are generated from nuclear power in France and from nuclear and other clean sources in Japan. EV GHG emissions are high in Washington, D.C. and Australia because large amounts of electricity are generated from coal in both places. The high GHG emissions in Boston are due to high per-mile EV electricity consumption and a large amount of electricity generated from oil. GHG emissions in Los Angeles are higher than those in the U.S., primarily because estimated per-mile EV electricity consumption in Los Angeles is higher than that in the U.S.

Among the three greenhouse gases, CO_2 emissions contribute to 93-98% of total EV GHG emissions, global warming potential-adjusted CH_4 emissions contribute to 1-6%, and global warming potential-adjusted N_2O emissions contribute to about 1%. Usually, if coal- and NG-fired power plants are the primary electricity source for EVs, global warming potential-adjusted CH_4 emissions contribute to over 5% of total GHG emissions.



Note: P.E. represents primary energy, E.P. represents energy products, and P.P. represents power plants.

Figure 3. EV Fuel Cycle Greenhouse Gas Emissions

Greenhouse Gas Emission Reductions by EVs

Figure 4 presents per-mile GHG emission reductions by EVs in each city or country. Reductions in GHG emissions due to use of EVs are achieved in all cities and countries analyzed. EV emission reductions range from about 15% in Washington, D.C. and Australia to nearly 100% in Norway and Chicago. The small EV emission reductions in Washington, D.C. and Australia occur because more than 80% of EV electricity is generated from coal in both places. The largest emission reductions in Norway and Chicago occur because virtually all EV electricity is generated from hydro-power in Norway and from nuclear power in Chicago. The significant EV emission reductions in France and Japan are due to use of nuclear power and other clean sources for power generation in both countries. The relatively high EV emission reductions in the U.K. and Boston are due to estimated high GHG emissions of baseline GVs, caused in turn by use of the NYCC. Higher EV emission reductions in the U.S. than in Los Angeles are due to both the use of nuclear power and other clean sources in the U.S., and the lower EV energy consumption for the FUDS compared with that of the LA-92.

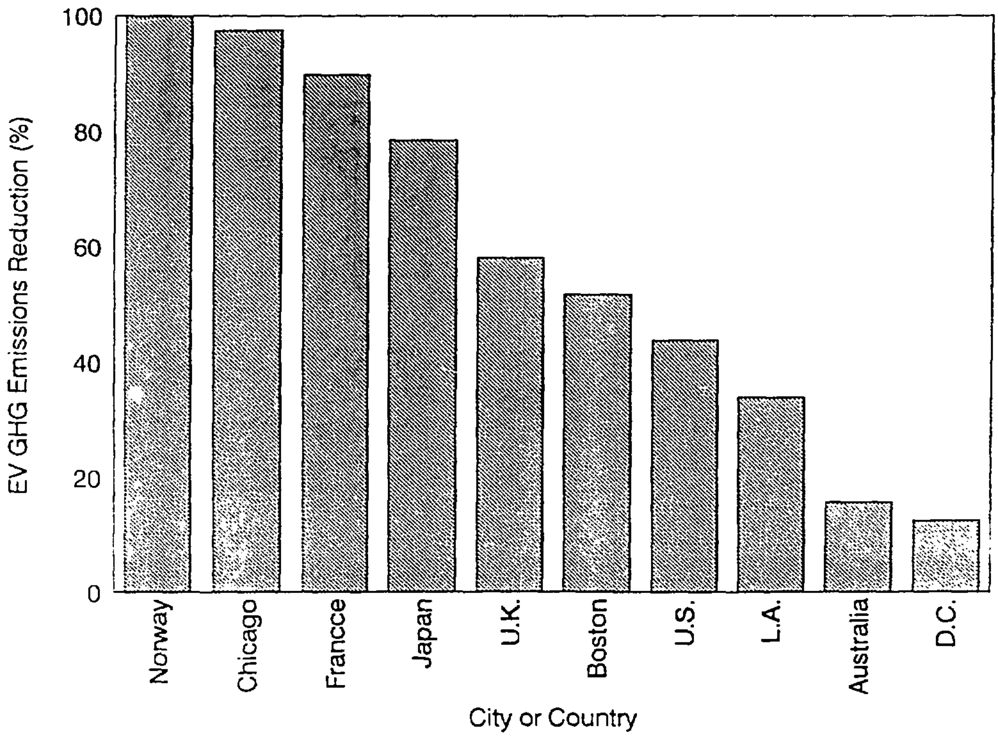


Figure 4. EV Greenhouse Gas Emission Reductions

Our results are consistent with those of some previous studies. The above cited U.S. Department of Energy study showed that with U.S. average power-plant mixes, EVs reduce per-mile CO_2 emissions by about 38% nationwide if EVs are energy-inefficient, and by almost 80% if EVs are energy-efficient (U.S. Department of Energy, 1993). Our study shows that EVs could reduce total fuel cycle GHG emissions in the U.S. by about 44%. Wang and Santini (1993) showed EV CO_2 reductions of 100% in Chicago and 0-70% in Los Angeles, depending on driving cycles applied. Our study estimates that EVs reduce energy cycle GHG emissions by 98% in Chicago and by 34% in Los Angeles.

Caveats

The results with respect to EV GHG emission reductions in this study indicate that the electric power-plant mix for EV recharge and the driving cycles used for estimating GV and EV energy consumption are two important factors in determining EV GHG emission reductions. In this study, we use estimated marginal power-plant mixes for Chicago and Los Angeles. However, we use average power-plant mixes for the remaining two U.S. cities and the six countries, because marginal power-plant mixes for these cities and countries are not available. Marginal power-plant mix for EV recharge in a region could be very different from the average power-plant mix in the region. For example, the U.S. Department of Energy study (U.S. Department of Energy, 1993) indicates that coal-fired power plants provide the greater portion of EV electricity in the U.S. under the marginal power-plant mix, but coal-fired power plants provide less than 50% of total electricity under the average power-plant mix. Because of this difference, the study estimates that EV emission reductions are significantly lower under the marginal power-plant mix than under the average power plant mix. Marginal power-plant mixes should be estimated and used for analyzing EV emission impacts.

In estimating GV and EV energy consumption, we choose for a given city or country a driving cycle that is developed or used in the city or country. We take the position that the driving cycle developed or used in a city or country represents trip characteristics of motor vehicles in the city or country. In reality, actual trip characteristics in a region could be significantly different from the driving cycle developed or used there. Consequently, GV and EV energy consumption could be different. In addition to the problem, there are no driving cycles for some cities or countries included in this study. For those cities or countries, we use driving cycles developed for larger geographic regions. For example, we apply the FUDS developed for the U.S. to Washington, D.C. and Chicago, and the ECE-15 to France, Norway, and the U.K. Trip characteristics between the two cities and among the three countries are certainly different from the generic driving cycles used. To accurately analyze EV emission impacts, city- and country-specific trip characteristics should be collected, and vehicle missions considered.

We analyze EV GHG emission reductions for six countries by using country aggregate data. EVs may not be introduced nationwide. Rather, they will very likely be introduced to major urban areas. The EV emission reductions between the U.S. and the four U.S. cities demonstrate that significant differences in EV emission reductions between a country and its major urban areas exist. Thus, nationwide EV emission reductions estimated in an aggregate way may not represent EV emission reductions in major urban areas. This is especially true for large countries, such as the U.S., Australia, and the U.K. To accurately estimate EV emission reductions where EVs are most likely to first be promoted and introduced, EV emission impacts should be analyzed for each major urban area.

CONCLUSIONS

Use of EVs in four U.S. cities (Boston, Chicago, Los Angeles, and Washington, D.C.) and in six countries (Australia, France, Japan, Norway, the U.K., and the U.S.) results in vehicle total fuel cycle GHG emission reductions. The largest EV GHG emission reductions occur in Norway, where hydro-power provides electricity for EVs, and in Chicago, where nuclear power provides electricity for EVs. High EV emission reductions are achieved in France and Japan, where large amounts of EV electricity are generated from nuclear power and other clean power sources. Moderate EV emission reductions occur in the U.K., Boston, the U.S., and Los Angeles, even though fossil-fuel power plants provide the greater portion of EV electricity. This results from the relatively high GHG emissions from GVs in these countries or cities. Small EV emission reductions are achieved in Australia and Washington, D.C., due to high EV emissions from coal-fired power plants there. The striking result of this study is that EVs achieve GHG emission reductions even in the areas where the greater portion of electricity is generated from coal- or oil-fired power plants. Such areas include Australia, Washington, D.C., and Boston.

Estimated per-mile GHG emissions from GVs and EVs show that use of different driving cycles makes a large difference in estimated GV and EV energy consumption, and thus in estimated GV and EV GHG emissions. GHG emission changes with driving cycles are larger for GVs than for EVs. Use of appropriate driving cycles representing actual vehicle trip characteristics is important in estimating EV GHG emission reductions.

The total fuel cycle GHG emissions estimated for both GVs and EVs indicate that GV operation contributes to the bulk of GV fuel cycle emissions, and power-plant operation contributes to the bulk of EV fuel cycle emissions. Primary energy recovery and processing contribute to a noticeable amount of GHG emissions. Transportation of fuels contributes to a minimal amount of GHG emissions.

Among the three greenhouse gases, CO_2 emissions are the largest contributor to total GHG emissions, accounting for more than 90% of total GHG emissions. Global warming potential-adjusted CH_4 and N_2O emissions together account for less than 10% of total GHG emissions.

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