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Emission Impacts of Electric Vehicles

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Emission Impacts of Electric Vehicles

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Alternative vehicular fuels are proposed as a strategy to reduce urban air pollution. In this paper, we analyze the emission impacts of electric vehicles in California for two target years, 1995 and 2010. We consider a range of assumptions regarding electricity consumption of electric vehicles, emission control technologies for power plants, and the mix of primary energy sources for electricity generation. We find that, relative to continued use of gasoline-powered vehicles, the use of electric vehicles would dramatically and unequivocally reduce carbon monoxide and hydrocarbons. Under most conditions, nitrogen oxide emissions would decrease moderately. Sulfur oxide and particulate emissions would increase or slightly decrease. Because other areas of the United States tend to use more coal in electricity generation and have less stringent emission controls on power plants, electric vehicles may have less emission reduction benefits outside California.

Internal combustion engine vehicles (ICEVs) are major contributors to air pollution. In 1987 in the United States, emissions from highway vehicles were 33.8 percent of total emissions of nitrogen oxides (NO_x), 24.0 percent of volatile organic compounds (VOCs), and 54.4 percent of carbon monoxide (CO).[1] In urban areas, the contribution of motor vehicles to air pollution was even greater. For example, in the Los Angeles area in 1985, highway vehicles contributed 60 percent of NO_x, 37.5 percent of CO, 46.4 percent of hydrocarbons (HCs), and 29 percent of sulfur oxides (SO_x) emissions.[2]

Most major metropolitan areas do not meet national ambient air quality standards (NAAQS) for one or more of the criteria pollutants. As a result, local, state, and the federal governments are adopting increasingly stringent rules to reduce emissions. Motor vehicles and motor fuels are a prime target. A major thrust of policy and regulatory initiatives is the replacement of petroleum fuels with cleaner-burning alternative fuels.

The most aggressive proposals are those in the Los Angeles area where the air quality management plan[2] adopted by the South Coast Air Quality Management District and the Southern California Association of Governments calls for 40 percent penetration of new light and medium duty vehicles, 70 percent penetration of new freight vehicles, and 100 percent penetration of new buses by "low-emitting" vehicles by the year 2000. Low-emitting vehicles are defined to be much cleaner burning gasoline and diesel-powered vehicles, or vehicles that operate on methanol, compressed natural gas, propane, and electricity. In late 1989, the California Air Resources Board (CARB) proposed new stringent emission standards to force the introduction of low-emission vehicles, ultra-low-emission vehicle, and zero-emission vehicles to California in the late 1990s.[3]

In this paper, we analyze changes in air pollutant emissions in California that would result from the replacement of gasoline-powered vehicles with electric vehicles (EVs). We estimate net changes in emissions attributable to EVs by comparing emissions of future gasoline-powered ICEVs that would be eliminated by using EVs with emissions from future power plants used to supply electricity to power EVs. We calculate emission impacts for California for 1995 and 2010.

Previous Studies

Several studies of the air quality impacts of EVs were conducted in the United States from the mid-1970s to the mid-1980s. Because they under-estimated emissions from gasoline vehicles and over-estimated emissions from power plants, some of the early studies concluded that the introduction of EVs would provide little or no emission benefits.

For instance, Hamilton et al.[4] in 1974 forecast only minor air quality benefits from the use of EVs, even when EVs accounted for 74 percent of autos in the Los Angeles area in the year 2000, primarily because the then newly-promulgated auto emission standards were expected to nearly eliminate vehicular air pollution. Marfisi et al.[5] in 1978 projected reductions in CO and HC, but increases in NO_x, SO_x, and particulate matter (PM) emissions, resulting from electrifying 10–14 percent of the passenger vehicle fleet in Los Angeles, Chicago, New York, and Washington, D.C., in the year 2000. Singh et al.[6] and General Research Corporation[7] in the early 1980s forecast lower HC, CO, NO_x, and PM emissions, but higher SO_x emissions of EV use in the year 2000. CARB[8] estimated in the mid-1980s that net reductions in the emissions of HC, CO, and NO_x would be high on a per-mile basis, and that the absolute amount of emission reductions were nearly proportional to EV market share in the South Coast Air Basin of California.

Implications

Proposed amendments to the Clean Air Act, and California's clean fuels and clean vehicles program require alternative fuels as a means of reducing pollution from the transportation sector. The use of electric vehicles will dramatically reduce hydrocarbon and carbon monoxide emissions, and in most cases will reduce emissions of nitrogen oxides. This analysis will help policy makers assess the potential of electric vehicles to reduce emissions from the transportation sector.

More recently, a study of EV emission impacts in the Los Angeles area finds large emission benefits for EVs,[9] but does not estimate actual in-use emissions from gasoline-powered ICEVs, and ignores refueling emissions at gasoline service stations and evaporative emissions from ICEVs.

Recent studies in Europe and Japan also consider EVs to be an effective option for achieving large emission reductions,[10-11] but these findings are specific to those regions—they depend principally upon the emission characteristics of vehicles and power plants in those regions. Emission rates for vehicles and power plants may vary by orders of magnitude in different regions. Our analysis is specific to California.

Analytical Approach

We consider five air pollutants in this paper: HC, CO, NO_x, SO_x, and PM. We consider neither CO_2 impacts of EVs because they have been addressed elsewhere,[12-13] nor benzene and other unregulated pollutants, because accurate data are not available. Only gasoline-powered light duty vehicles, automobiles and light trucks (less than 6000 pounds gross vehicle weight) are analyzed; diesel vehicles are excluded because diesel light-duty vehicles accounted for only about 0.1 percent of total sales in 1988.[14]

Electric vehicles do not emit air pollutants, but power plants do. Accordingly, using a comparative approach, we first calculate emission factors of the five pollutants for gasoline-powered ICEVs, and for power plants supplying electricity to EVs. We then estimate emission changes associated with EV use for the five pollutants.

Over time, changes occur in emission control technologies, fuel mix of power plants, emission rates of ICEVs, and electricity consumption rates of EVs. The calculation of EV emission reductions therefore must be targeted to particular years: we use 1995 and 2010.

On the vehicle side, we propose an EV market penetration scheme to calculate the average emission factors of the ICEVs which will be replaced by EVs. We assume that EVs will start to be introduced into the vehicle population in a specific year, and continue to be introduced after the starting year. Based on this assumption, in an early target year, EVs replace newer ICEVs, not older ones. In a later target year, EVs already in the fleet could replace older as well as newer ICEVs. This assumption is important because newer ICEVs have much lower emissions than older ICEVs, due to continuing technology improvements and anticipated tightening of standards, and due to large emission increases for older vehicles from vehicle deterioration. The details of this approach are presented in a later section.

Emissions of power plants are primarily a function of fuel mix of electricity generation and emission control technologies deployed on power plants. We calculate emission impacts of EVs for different types of power plants, and then use fuel mix projections for utility systems to calculate system-average emission factors. We establish scenarios for emission control technologies for power plants, and for electricity consumption by EVs. Results of EV emission impacts are presented as per-mile emission reductions (for full details on data and calculations, see Wang et al;[15] some refinements were made in the analytical approach).

Emission Factors of ICE Automobiles and Light Duty Trucks (LDTs)

California first regulated vehicle emission rates in 1965, five years before the federal Clean Air Act gave the Environmental Protection Agency (EPA) authority to regulate vehicle emission rates nationwide. Currently, EPA establishes vehicle emission standards for the nation, while CARB continues to establish more stringent standards for California. CARB regulates emission rates of HC, CO, and NO_x, while EPA regulates HC, CO, NO_x, PM, and evaporative HC.

CARB and EPA both set emission standards for vehicles that have traveled 50,000 miles (commonly called 50,000-mile emission standards). CARB also sets 100,000-mile emission standards. The intent of the 50,000 and 100,000 mile-standards is to account for deterioration of emission control equipment.

EPA and CARB certify emission rates of new vehicles through laboratory procedures. This certification process insures that new vehicles meet emission standards. However, laboratory-certification rates of vehicle emissions are lower than actual in-use emission rates due to improper maintenance of in-use vehicles by individual drivers, better quality fuels used in the certification process, in-use driving cycles different from the testing cycles, and a greater potential for deterioration of catalysts in actual use.[16-17] Thus, neither emission standards nor certification rates represent actual in-use emission rates. In the following sections, we derive in-use emission rates that more accurately represent ICEV emissions.

EPA calculates in-use emission factors of HC, CO, and NO_x with a computer program—MOBILE. The new version is MOBILE4.[18] MOBILE accounts for many variables including environmental temperature; altitude; vehicle speed; percentage of VMT associated with cold start, hot start, and stabilized conditions; fuel type; and vehicular emission standards. In California, vehicle emission rates are calculated by using the EMFAC computer model developed by CARB—California's version of EPA's MOBILE. The latest version of EMFAC is EMFAC7D which corresponds to MOBILE3—the precursor of MOBILE4.[19-20] The new version, EMFAC7E, is expected to be available soon. We use EMFAC7D outputs for our calculations, since we focus on California.

Exhaust Emission Rates of HC, CO, NO_x, and PM

To estimate emission reductions of EVs, one needs to calculate emission factors of the ICEVs which will be replaced by EVs (referred to as *replaced* ICEVs). We calculate fleet emission factors of these four pollutants for replaced ICEVs for two target years: 1995 and 2010. To determine the model-year mix of the replaced ICEV fleet, we specify scenarios of model-year mix of the EV fleet in a target year. The model-year mix of the EV fleet becomes the model-year mix of the replaced ICEV fleet. We assume EVs will be introduced in 1991, and posit increasing numbers of EVs in each subsequent year until 2000, after which the number of EVs introduced annually remains constant. Thus, for 1995, the EV fleet (and the replaced ICEV fleet) will include model-year vehicles from 1991 to 1995, and for 2010, from 1991 to 2010.

To calculate replaced ICEV fleet emission factors, we use EMFAC7D's zero-mile emission rates, emission deterioration rates, and cumulative mileage of model-year vehicles in the target year. Then, replaced fleet emission rates in the two target years are calculated by using annual vehicle miles traveled (VMT) by each model-year vehicle and percentages of each model-year electric vehicles out of all model-year electric vehicles in each target year. Emission factors for automobiles and LDTs are calculated separately. The replaced fleet emission factor, EF, in grams per mile (gpm), is calculated for each pollutant as follows:

$$EF_k = \sum_{i=1991}^{k} EER_{i,k} * VMT\%_{i,k} \qquad (1)$$

Where:

EF_k = replaced fleet emission factor for target year k (gpm)

k = target year, 1995 and 2010

$EER_{i,k}$ = exhaust emission rate of model-year i ICEVs in target year k (gpm)

$VMT\%_{i,k} = VMT$ of model-year i EVs as percent of total VMT of all model-year EVs in target year k.

And:

$$EER_{i,k} = ZMER_i + (DR_i * CUMIL_{i,k}) \qquad (2)$$

Where:

$ZMER_i$ = zero-mile emission rate of model-year i ICEVs (gpm, from EMFAC7D)

DR_i = emission deterioration rate of model-year i ICEVs (gpm/10,000 miles, from EMFAC7D)

$CUMIL_{i,k}$ = cumulative miles of model-year i ICEVs in target year k (in 10,000 miles)

And:

$$CUMIL_{i,k} = \sum_{m=i}^{k} VMT_{i,m} \qquad (3)$$

Where:

$VMT_{i,m}$ = annual VMT of a model-year i ICEV in year m (from EMFAC7D)

The EV VMT percentage calculation formula is:

$$VMT\%_{i,k} = \frac{(\% \text{ of EVs})_{i,k} * \text{Annual } VMT_{i,k}}{\sum_{m=1991}^{k} ((\% \text{ of EVs})_{m,k} * \text{Annual } VMT_{m,k})} \qquad (4)$$

Where:

$VMT\%_{i,k} = VMT$ of model-year i EVs as percent of total VMT of all model-year EVs in target year k

$(\% \text{ of EVs})_{i,k}$ = Percentage of model-year i EVs relative to all model-year EVs in target year k

Annual $VMT_{i,k}$ = Annual VMT of model-year i ICEVs in target year k (from EMFAC7D)

CARB has adopted new emission standards for non-methane HC of 0.25 grams per mile and CO of 3.4 grams per mile for model-year automobiles and light duty trucks from 1993 and on.[21] EMFAC7D does not incorporate these newly-adopted standards. We use these standards to adjust EMFAC7D's $ZMER_i$ of HC and CO for each model-year ICEVs after 1993. Furthermore, since more stringent emission standards are likely to be implemented in the future,[22] we assume that the $ZMER_i$ of model-year ICEVs will be reduced by 10 percent in every 5 years between 1996 and 2010. We further assume that DR_i (the deterioration rate) for each model-year vehicles will be reduced 10 percent every 5 years between 1996 and 2010, to account for the effect of vehicle inspection/maintenance (I-M) programs (the DR_i of EMFAC7D does not account for I/M program).

Diurnal and Hot Soak Evaporative Emissions of HC

Evaporative HC emissions, which are caused by the evaporation of gasoline from the fuel tank, the fuel distribution system, and the carburetor, are analyzed as diurnal, hot soak, and running evaporative emissions. Diurnal emissions are those that occur from one day to the next due to the heating of the fuel in the day and the cooling at night. These emissions are independent of vehicle use. When hot vapors are emitted at the end of the trip, hot soak emissions occur. Running losses are evaporative losses from the vehicle when it is moving. EMFAC7D estimates diurnal and hot-soak emissions, but not running evaporative emissions.

EMFAC7D calculates a zero-mile diurnal emission rate and hot soak emission rate as well as deterioration rates for each model-year vehicle up to 1995. We use EMFAC7D's

zero-mile and deterioration rates to calculate replaced fleet diurnal and hot soak emission rates in those two target years, in a way similar to the calculation of exhaust emission rates. EPA proposes a 21.7 percent reduction in RVP (Reid Vapor Pressure) of gasoline after 1992.[23] CARB proposes new standard of 8 psi (pounds per square inch) of gasoline RVP after 1994.[24] Since a lower RVP results in lower HC evaporation emissions, we assume a 10 percent reduction in zero-mile hot soak and diurnal emissions for each subsequent 5-year period after 1995 until 2010. We also assume that deterioration rates of evaporative emissions are reduced 10 percent for each 5 years of the same period.

To calculate replaced fleet diurnal emissions (grams/day) and hot soak evaporative emissions (grams/trip), we use the following data. The percentage of each model-year EV to all model-year EVs in a target year is used to calculate average diurnal evaporative emissions, because diurnal emissions depend on the number of vehicles, not the miles driven. We use the percentage mix of each model-year EV relative to all model-year EVs and annual VMT of each model-year vehicle in a target year as the weighing factors to calculate fleet average hot soak emissions. Diurnal and hot soak emissions for both automobiles and LDTs are calculated separately.

The HC diurnal emission rate is in grams per day, and the hot soak emission rate in grams per trip. We use the following formula to convert both into grams per mile:

$$ER = (trips/d * ER_{hs} + ER_{di})/(miles/d) \qquad (5)$$

Where:

ER = diurnal and hot soak evaporative emission rate together in gpm

$Trips/d$ = trips per day per vehicle (3.5 for automobiles and 3.6 for LDTs[25])

ER_{hs} = hot soak evaporative emissions in grams per trip

ER_{di} = diurnal evaporative emissions in grams per day

$Miles/d$ = miles traveled per day per vehicle (26 for automobiles and 27.5 for LDTs[25])

Running Evaporative Emission of HC

Recently it has been suggested that HC running evaporative emissions are a significant contributor to total evaporative emissions. Simkins[26] concluded that running evaporative emissions are about 40–45 percent of the total evaporative HC emission on a gpm basis. EPA has incorporated running evaporation emissions into MOBILE4, and CARB is going to incorporate running evaporation emissions into EMFAC7E. EPA has found that running evaporative emissions, using gasoline of RVP ranging from 7.0 to 11.7, and with fuel injection systems, are on average 0.067 gpm for new automobiles and 0.08 gpm for new LDTs,[27] which is consistent with Simkins' result. We use EPA's estimates of running evaporative rates for up to 1995, and assume a 10 percent reduction in running emissions in each subsequent 5-year period until 2010, because a lower RVP of gasoline in the future will reduce running evaporative emissions from vehicles.

Evaporative Emissions of HC at Fuel Stations and Bulk Plants

There are two sources of evaporative emissions at fuel stations. One is associated with the delivery of gasoline from trucks to underground storage tanks (delivery emissions), and the other is associated with the delivery of gasoline from underground tanks to vehicle tanks (refueling emissions). In both refueling processes, the entering fuel displaces the gasoline vapors that are in the tank and forces them into the air (if there is no vapor recovery control). Braddock et al.[28-29] found that HC refueling evaporative emissions ranged from

2.90 to 7.41 grams per gallon of gasoline, with an average of 4.69 grams/gallon. Sierra Research Inc.[17] reports that the uncontrolled delivery emissions are 4.76 grams per gallon, and uncontrolled refueling emissions 4.86 grams per gallon, for a total of 9.62 grams per gallon.

Technologies to control the delivery emissions from delivery trucks into underground tanks, called stage I technologies, have been employed in most non-attainment areas of the country. Technologies to control the refueling emissions from underground tanks to vehicle tanks, called stage II technologies, at present are employed only in California. Delivery and refueling emissions with both stage I and stage II technologies are much lower—only 0.62 grams/gallon.[17] We use these controlled emissions for 1995.

HC emissions also occur in bulk plants where gasoline is stored and delivered to truck tanks. The HC emissions at bulk plants, from "breathing" and from filling and emptying the tanks, are about 0.19 gram/gallon.[30] We add refueling emissions of gasoline stations and bulk plants together, for a total of 0.81 grams/gallon, for the year 1995.

After 1995, we assume a 10 percent reduction in refueling emissions for each 5-year period until 2010, due to more stringent refueling emission control technologies and lower RVP of gasoline. These refueling emissions are divided by fuel economy of replaced ICEV fleet in the two target years to achieve refueling emissions in gpm.

Table I. Replaced fleet average fuel economy, miles per gallon.

Target year	1995	2010
Automobiles	34.2	43.3
LDTs	25.1	31.0

Based on EPA's fuel economy tests of various model-year vehicles,[14] and Difiglio et al. study of the fuel economy of future automobiles,[31] we project the fuel economy of the replaced ICEV fleet in 1995 and 2010.* Projected fuel economy of replaced ICE automobile and LDT fleets is presented in Table I.

Our HC emission factor now includes exhaust emissions, evaporative emissions (diurnal, hot soak, running loss), and gasoline station and bulk plant evaporative emissions.

SO$_x$ Emission Factors

EMFAC7D does not calculate vehicle SO$_x$ emission factors. We calculate SO$_x$ emissions by assuming that all sulfur in gasoline is converted into SO$_2$ during the combustion of gasoline. The sulfur content of gasoline fuel is about 0.03 percent by weight.[32] SO$_2$ emissions per gallon of gasoline are therefore:

$$2798 \ (gm/gal) * 0.0003 * 64/32 = 1.6788 \ (gm/gal)$$

where:

2798 = grams/gallon of gasoline

64 = molecular weight of SO$_2$

32 = molecular weight of sulfur

By using the replaced fleet fuel economy in Table I, we calculate the emission factor of SO$_2$ in gpm for the two target years.

Emissions from Refinery Plants

The EPA[1] calculates emissions in gigagrams per year for the U.S. petroleum refinery industry, using AP-42 emission

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* The model of detailed projections of automobile and LDT fuel economy is available from the authors on request.
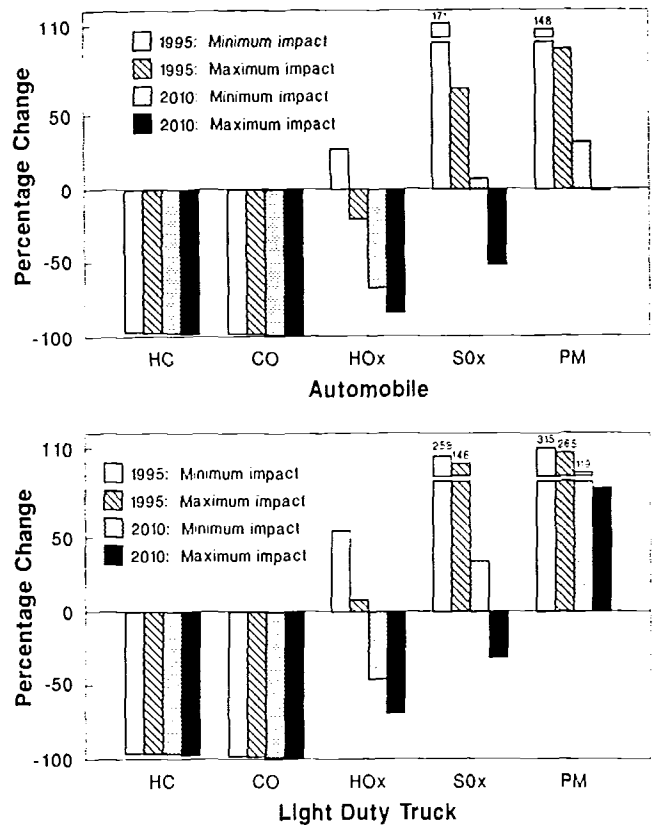

Figure 1. Emission impacts of electric vehicles relative to gasoline-powered vehicles, percentages, per mile, California.

factors for uncontrolled refinery process units and industrial boilers,[33] data on national refinery capacity by type of process unit,[34] and data on actual emissions from controlled refinery process units (as reported by air pollution control districts). To obtain grams of pollutant emitted per gallon of gasoline produced, we multiplied the EPA's calculated 1987 refinery emissions by 46.8 percent[35] (gasoline production as a percentage of all refinery end-products by volume), and divided by 1987 refinery gasoline production of 104.873 billion gallons.[35] To project gasoline refinery emission factors in 1995 and 2010, we assume 10 percent reduction in emission factors in each 5-year period between 1987 and 2010. We then use the fuel economy of the replaced ICEV fleet (Table I) to calculate refinery emission factors in grams per mile.

The calculated fleet ICEV emission factors of HC, CO, NO$_x$, SO$_x$, and PM are presented in Table II. We observe that HC, CO, and NO$_x$ exhaust emissions of the replaced ICEV fleet in 2010 are greater than those in 1995. This is because the 2010 replaced ICEV fleet contains older ICEVs (1991 to 2010 model-year ICEVs) than the 1995 replaced ICEV fleet does (1991 to 1995 model-year ICEVs), and older ICEVs have higher exhaust emissions than newer ICEVs do, due to their emission deterioration rates.

Power Plant Emission Factors

We calculate EV emission factors as follows. First, the emission factors for each type of power plant without emission control technologies are specified. Second, current actual emission factors of power plants are estimated, using data from the National Emission Data System. Third, the penetration of future emission control technologies for each type of power plant, each with different emission reduction potential, are specified for 1995 and 2010. Forth, the energy mix of electricity generation in utility systems is projected, and utility system average emission factors are calculated.

Finally, using the projection of EV electricity consumption per mile, we calculate EV emission factors.

Emission Factors of Uncontrolled Power Plants

Power plant emissions vary greatly, depending on the type of fuel and combustion technology used in the plant. We analyze emissions from coal, gas, and oil plants, separately. Hydropower, solar power, and nuclear power are excluded because they do not generate air pollutants. Biomass and geothermal are excluded because of data problems and because they account for a very small portion of electricity generation.

Emission factors for various types of uncontrolled plants are presented in Table III.

Emission Factors of Controlled Power Plants

In its National Emissions Data System (NEDS), EPA calculates emissions in gigagrams for each type of power plants, using AP-42 uncontrolled emission factors, annual fuel input, and data on emission control technologies deployed in current power plants.[1] Using emission estimates in NEDS, and EIA's data on fuel input to power plants,[40] we

Emission Factors of Future Controlled Power Plants

We calculate future emission factors by starting with current actual emission factors and positing emission control scenarios. Table IV is a list of current and future emission control technologies for power plants and their emission reduction potential.

We discuss the emission control technologies listed in Table IV elsewhere.[15] Since there are uncertainties about which emission control technologies will be used in power plants, we have created two emission control scenarios: a less stringent and a more stringent emission control strategy for power plants. A higher percentage of power plants are assumed to have the more effective emission control technologies under the more stringent strategy than under the less stringent strategy. Our scenario assumptions regarding the future deployment of these technologies in power plants are presented in Table V.

Emission factors in Lb/MMBtu fuel input must be converted to emission factors in grams/Kwh electricity output, and this calculation requires data on power plant conversion efficiencies. Conversion efficiencies for current plants are about 30–35 percent;[41] we used 33 percent for 1995. Conversion efficiencies of future power plants will be somewhat greater; we use a 38 percent factor for 2010.[41] A sensitivity

Table II. Emission factors of replaced ICEV fleet, California, grams per mile.

		AUTO		LDT	
		1995	2010	1995	2010
HC	Exhaust	0.290	0.632	0.423	0.667
	Evaporation[a]	0.141	0.117	0.161	0.131
	Refueling[b]	0.024	0.014	0.032	0.019
	Refinery	0.135	0.077	0.184	0.108
	Total	**0.590**	**0.840**	**0.800**	**0.925**
CO	Exhaust	3.592	8.861	5.789	9.369
	Refinery	0.070	0.040	0.096	0.057
	Total	**3.662**	**8.901**	**5.885**	**9.426**
NO$_x$	Exhaust	0.375	0.767	0.557	0.804
	Refinery	0.041	0.024	0.056	0.033
	Total	**0.416**	**0.791**	**0.613**	**0.837**
SO$_x$	Exhaust	0.049	0.038	0.067	0.054
	Refinery	0.170	0.098	0.232	0.137
	Total	**0.219**	**0.136**	**0.299**	**0.191**
PM	Exhaust[c]	0.010	0.010	0.010	0.010
	Refinery	0.003	0.002	0.004	0.002
	Total	**0.013**	**0.012**	**0.014**	**0.012**

[a] Includes diurnal, hot soak, and running evaporative emissions.
[b] Includes evaporative emissions in fuel stations and bulk plants.
[c] EMFAC7D assumes same PM exhaust emission rate for automobiles and LDTs until the year 2025, with a PM emission deterioration rate of zero.

calculate 1987 actual emission factors of power plants in pounds per MMBtu fuel input. Our calculated 1987 actual emission factors indicate that actual NO$_x$ emission rate of coal plants in 1987 was 45.2 percent lower than the uncontrolled NO$_x$ emission factor; for oil plants, 17.6 percent lower; and for natural gas plants, 19.8 percent lower. The actual SO$_x$ emissions from coal plants in 1987 was 23 percent lower than the uncontrolled SO$_x$ emission factor, and the actual PM factor was 98.2 percent lower. These reductions show the degree of the emission control technologies currently employed in power plants. The 98.2 percent PM emission reduction in coal plants implies that virtually all coal plants have highly effective PM control technologies, which is consistent with EIA's survey data.[40] We calculate current emission factors of power plants by using uncontrolled emission factors in Table III and these emission reductions.

analysis indicated that varying the average conversion efficiencies by 2 percent had little effect on EV emission factors.[15]

Having determined current actual emission factors, the mix of emission control technologies and their respective emission reductions (Table IV and V) for future power plants, and power plant conversion efficiencies, we next calculate future controlled emission factors in grams/kwh for each type of power plant. The formula converting current actual emission factors in Lbs/MMBtu fuel input to future controlled emission factors in gram/Kwh electricity output is:

$$EF_{ele} = EF_{fuel} * \left(\sum_i (1 - ER_i) * K_i + \left(1 - \sum_i K_i \right) \right)$$
$$* L1/L2/CE \quad (6)$$

Table III. Emission factors of uncontrolled power plants (Lb/MMBtu, fuel input).

	Gas-fired turbine[a]	Gas-fired boiler[b]	Oil-fired boiler[c]	Conventional coal plants[d]	Coal-fired CFB combustors[e]	IGCC coal plant[f]
HC	0.041	0.002	0.044	0.005	0.07	NA[g]
CO	0.112	0.039	0.052	0.029	0.06	0.004
NO_x	0.402	0.535	0.459	1.627	0.2	0.07
SO_x	0.0006[h]	0.0006	1.020[i]	2.468[j]	0.93[k]	0.018
PM	0.014	0.003	0.082[l]	3.309[m]	0.02	0.004

[a] From EPA.[33] We use 1,028 Btu per cubic feet of natural gas to convert emission factors in Lb/feet^3 to Lb/MMBtu.

[b] From EPA.[33] We use emission factors of gas-fired boilers with fuel input greater than 100 MMBtu/hr (utility boilers). We use 1,028 Btu per cubic feet of natural gas to convert emission factors in Lb/feet^3 to Lb/MMBtu.

[c] From EPA.[33] We assume that No. 6 residual oil is burnt in oil-fired boilers. We use 149,626 Btu per gallon of residual oil to convert emission factors in Lb/gallon to Lb/MMBtu. Emissions of oil-fired boilers include emissions of petroleum refinery in refinery plants as well as the emissions of electricity generation in power plants.

[d] From EPA.[33] We use emission factors for pulverized bituminous and subbituminous coal-fired units with wet bottom technology. We use 20.109 MMBtu per short ton of coal to convert emission factors in Lb/ton to Lb/MMBtu.

[e] From CARB.[36] The emission factors of coal-fired circulating fluid-bed (CFB) combustor are derived from the data submitted on air pollution permit applications for two coal power plants, Corn Products and Cogeneration National Facilities in Stockton, California.

[f] Emission data of a coal integrated gasification combined-cycle system at Cool Water, California.[37-38]

[g] Not available.

[h] The SO_x emission factor of gas-fired turbines can be calculated as $0.914*S$, where S is the percent sulfur content of natural gas by weight. We use sulfur content of 0.0007% for natural gas.[36]

[i] The SO_x emission factors of oil-fired boilers can be calculated as $1.069*S$, where S is the percent sulfur content of residual oil. We use the national average of sulfur content of residual oil of 0.91% by weight.[39]

[j] The SO_x emission factor of conventional coal-fired plants can be calculated as $1.87*S$, where S is the percent sulfur content of coal by weight. We use the national average of sulfur content of coal 1.32% by weight.[39]

[k] The SO_x emission factor of CFB combustors can be calculated as $1.69*S$, where S is the percent sulfur content of coal by weight. CARB assumes that low sulfur content coal will be used in CFB combustors. We use CARB's assumption of 0.55% of sulfur content of "clean" coal.[36]

[l] The PM emission factor of oil-fired boilers can be calculated as $0.067\%*S+0.02$, where S is percent sulfur content of residual oil. We use national average of percent sulfur content of residual oil of 0.91%.[39]

[m] The PM emission factor of conventional coal-fired plants can be calculated as $0.332*A$, where A is the percent ash content of coal by weight. We use national average of ash content of 9.98% for coal.[39]

Where:

EF_{ele} = future controlled emission factor in grams per Kwh electricity output

EF_{fuel} = current emission factor in lbs per MMBtu fuel input

ER_i = emission reduction rate of technology i (see Table IV)

K_i = the share of technology i in power plants (see Table V), specified for both emission control scenarios

L1 = 454 grams per pound

L2 = 293.1 Kwhs per MMBtu

CE = power plant conversion efficiency, 35 percent for 1995 and 38 percent for 2010

Energy mix. The next step is to determine the percentage of primary energy sources (energy mix) in California's electricity generation system so that utility system average emission factors can be estimated. We assume that EVs will use "average" electricity in the sense that we do not account for time-of-day usage. Certainly, EVs will use more electricity from off-peak facilities if price incentives are provided for off-peak recharge. However, at present, it is difficult to determine which facilities will provide electricity for EVs, and thus we use the forecasted energy mix of utility systems (assuming no EVs) to calculate utility average EV emission factors.

Based on an earlier discussion, we specify four categories of electricity feedstocks: natural gas, oil, coal, and other. "Other" is defined as having zero emissions, and includes hydropower, wind, biomass, geothermal, solar, and nuclear. Biomass and geothermal clearly generate emissions. However, biomass and geothermal energy resources account for a modest portion of electricity generated and may have lower emission factors. For example, for California in 1995, it is forecasted that 4 percent of the electricity will be generated from biomass and 6 percent from geothermal.[42]

Projections of primary energy source supplies for electricity generation for California are presented in Table VI. The coal category includes California-owned power plants outside the state (Virtually, all of the coal plants owned by California's utilities are located outside California), as well as about 20 percent of purchased electricity from the Northwest and 70 percent from the Southwest.[43] The remainder of the purchased electricity is generated from hydropower and nuclear.

In order to show the importance of energy mix in determining EV emission impacts, we also present the projections of energy mix for the United States. From Table VI, we see that the nationwide energy mix of electricity generation is much different from that of California. About 40 percent of California electricity is generated from natural gas, while about half of U.S. electricity is generated from coal. Since natural gas burns much cleaner than coal, this implies that

EV emission reduction benefits will be greater in California than elsewhere in the United States.

Projected mix of gas turbines and steam boilers in natural gas plants. The natural gas supply for electricity generation must now be translated into specific types of gas-fired plants: steam boilers and gas turbines. Gas turbines are expected to increase their share of power plant generation capacity because improvements in gas turbine technology, such as steam-injected and intercooled steam-injected gas turbines, will lead to lower cost and less pollutants.[45] Also, the expected increase in future cogeneration power plants will expand the use of gas turbine technology. The projected percentages of steam boiler and gas turbine plant capacity for 1995 and 2010 for California are shown in Table VII.

Projected mix of coal combustion technologies. Among the three coal combustion technologies, IGCC is the cleanest, and CFB combustors the second. As indicated in Table VII, we expect the share of CFB and IGCC systems to increase over time, due to increasingly stringent air pollution regulations and their greater ability to reduce emissions. The market share of the third major option, conventional combustion, is likely to diminish. Although the assumed 35 percent of CFB systems in 2010 in California seems high, the absolute capacity of CFB plants will still be small in California, because the percentage of electricity generated from coal in California is and will be small (about 10 percent of electricity generation).

We treat power plant emission factors reported by EPA and CARB as lifetime averages rather than "year zero" emission rates. If they are year zero emission factors, the question of emission deterioration arises. For two reasons, we feel it is reasonable to treat power plant emission rates as lifetime averages. First, the EPA data for uncontrolled emissions are based on an extensive review of published test results. While the tests are not explicitly chosen to get a representative sample of power plant ages, operating conditions, etc., there is no reason to believe the tests are seriously misrepresentative of new plants and old plants. Second, power plant emission rules do not allow deterioration as do the 50,000 mile standards for vehicles. A plant must meet emission standards throughout its life, and is checked regularly for compliance. We assume no emission deterioration in power plants.

EV Emission Factors

Emission factors of power plants in grams/Kwh are now translated into emission factors of EVs in grams/mile using estimates of EV electricity consumption per mile from the outlet. EV energy efficiencies are sensitive to the characteristics of the vehicle, especially the battery. Since future EV technologies are uncertain, based on a previous analysis,[41] we estimate high and low EV electricity consumption rates as shown in Table VIII. These consumption rates are averages over all driving conditions, estimated separately for electric automobiles and electric LDTs. The EV electricity consumption rates presented in Table VIII include EV charger and battery efficiencies. Sensitivity analysis indicates that EV electricity consumption rates are important in determining EV emission impacts.

As a final step, electricity consumption estimates in Table VIII are increased by 9 percent to take into account transmission losses between the power plant and wall outlet.[44]

Emission Impacts of EVs

Calculated EV emission impacts in California are presented in Figure 1 for 1995 and 2010. The maximum reduction scenario in the charts combines more stringent power plant emission controls and low EV electricity consumption rates, while the minimum reduction scenario combines less strin-

Table IV. Emission control technologies and their potential emission reductions for electric power plants. "Current" control technologies will be installed on power plants before 1995, and "future" control technologies after 1995. Source: CARB.[36]

Current control technologies		Future control technologies	
Technology	Emission reduction (%)	Technology	Emission reduction (%)
Gas-fired turbine			
Water injection for NO$_x$	70	Water injection for NO$_x$	82
SCR for NO$_x$	80	SCR for NO$_x$	90
Coal-fired plants			
Thermal DeNO$_x$ for NO$_x$	80	Thermal DeNO$_x$ for NO$_x$	80
SCR for NO$_x$	80	SCR for NO$_x$	90
Limestone injection for SO$_x$	95	Limestone injection (95%) with spray dryer for SO$_x$ (50%)	97.5
Gas-fired boilers			
SCR for NO$_x$	80	SCR for NO$_x$	90
Flue-gas recirculation for NO$_x$	70	Flue-gas Recirculation for NO$_x$	70
Oil-fired boilers			
SCR for NO$_x$	80	SCR for NO$_x$	90
Flue-gas recirculation for NO$_x$	70	Flue-gas Recirculation for NO$_x$	70
Scrubber for SO$_x$	90	Scrubber for SO$_x$	95

gent controls and higher EV electricity consumption (based on Tables V and VIII). The estimates in the two charts, one for automobiles and another for LDTs, are calculated on a vehicle-mile basis.†

For automobiles in both scenarios, EVs reduce HC and CO emissions by over 96 percent in 1955 and 97 percent in 2010, on a per-mile basis. EVs increase NO$_x$ emissions by 27 percent in 1995 under the worst case scenario and reduce NO$_x$ emissions by about 20 percent in 1995 under the best case. EVs reduce NO$_x$ emissions by over 65 percent in 2010. EVs are thus an attractive strategy for reducing HC, CO, and to a less extent, NO$_x$ *emissions*, and therefore CO, NO$_2$, and ozone *concentrations* in the atmosphere.

Electric automobiles would increase SO$_x$ and PM emissions in 1995 and in 2010 under the worst case scenario. SO$_x$ and PM emissions would increase in 1995 under the best case scenario. However, under the best scenario, SO$_x$ emissions would actually *decrease* by 50 percent in 2010, and PM emissions would be about the same as gasoline-powered automobiles. Note, though, that whatever the per-mile changes in SO$_x$ and PM emissions due to EVs, they are relatively unimportant because automobiles contribute only 6.5% of SO$_x$ and 1.7 percent of PM emissions in California.[46] Furthermore, based on EMFAC7D,[19] 95 percent of automobile PM emissions are from tirewear, which are about the same for EVs as for ICEVs. Therefore, the effects of EVs on the *absolute* amount of SO$_x$ and PM emissions in California would be negligible.

Emission impacts of electric light duty trucks can be observed in Figure 1. HC and CO emission reduction benefits of electric light duty trucks are similar to those of electric automobiles. However, NO$_x$, SO$_x$, and PM emissions due to use of electric light duty trucks are greater than those due to electric automobiles, mainly due to more electricity consumption per mile of electric light duty trucks.

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† We also calculated emission impacts of electric automobiles and LDTs by type of electricity plant (coal, gas, and oil) for two scenarios of power plant emission control and two scenarios of EV electricity consumption per mile. Detailed results are available from the authors on request.

Table V. Percentage of power plants deploying emission control technologies under two emission control scenarios. For coal plants, we assume that the emission control technologies are applied to conventional coal plants and CFB coal plants, but not IGCC systems.

Less stringent control strategy		More stringent control strategy	
Gas turbines			
NO_x:		NO_x:	
1995: SCR	10	1995: SCR	30
Water injection	20	Water injection	20
2010: SCR	30	2010: SCR	50
Water injection	20	Water injection	20
Coal plants			
NO_x:		NO_x:	
1995: SCR	10	1995: SCR	30
Thermal $DeNO_x$	20	Thermal $DeNO_x$	20
2010: SCR	30	2010: SCR	50
Thermal $DeNO_x$	20	Thermal $DeNO_x$	20
SO_x: Limestone injection		SO_x: Limestone injection	
1995:	30	1995:	50
2010:	70	2010:	90
Gas-fired boilers			
NO_x:		NO_x:	
1995: SCR	10	1995: SCR	30
FGR	30	FGR	30
2010: SCR	30	2010: SCR	50
FGR	30	FGR	30
Oil-fired boilers			
NO_x:		NO_x:	
1995: SCR	10	1995: SCR	30
FGR	30	FGR	30
2010: SCR	30	2010: SCR	50
FGR	30	FGR	30
SO_x: Scrubbers		SO_x Scrubbers	
1995:	10	1995:	30
2010:	50	2010:	70

To test the sen   y of the results with respect to energy mix, and to give some sense of the EV emission impacts likely to be experienced elsewhere in the United States, we substituted the projected U.S. energy mix (see Table VI) for the California energy mix for 1995 and 2010. The results are presented in Table IX. As before, HC and CO emissions are dramatically reduced under all conditions, but with the U.S. energy mix, NO_x benefits are not as great. SO_x and particulate emissions increase under all conditions because more coal is used in the United States than in California for electricity generation. This energy mix analysis indicates that even with much greater use of coal, EV use will still reduce CO and ozone pollution, but will cause some increases in particulates and SO_x on a per-mile basis. However, since PM and SO_x emissions from automobiles and LDTs are a small percentage of total PM and SO_x emissions in the United States as well as in California,[1] EVs would cause minor increase in total nationwide PM and SO_x emissions.

Discussion

We note that a recent study of EV air quality impacts referred to earlier came to similar conclusions, although they used more simplistic assumptions.[9] They assumed that 50,000 mile emission standards represent in-use emissions of vehicles, apparently ignored evaporative, refueling emissions, and refinery emissions, used 1987 power plant emission factors to represent 2010, and did not specify energy

Table VI. Projected mix of energy resources for generating electricity, percentages.

	California		U.S.A.	
	1995[a]	2010[b]	1995[c]	2010[d]
Gas	36.2	47.8	11.0	15.0
Oil	5.0	5.0	7.1	10.0
Coal	12.3[e]	9.2[e]	52.7	45.0
Other[f]	46.5	38.0	29.2	30.0

[a] CEC's projection.[42]
[b] CEC's projection for 2007, without modification.[42]
[c] EIA's projection.[44]
[d] Our projection.
[e] Virtually, all of California's coal plants are located out of the state. Also, about 20% of purchased electricity from the Northwest is generated from coal, and 70% from the Southwest.[43] We include both the coal plants owned by California utilities and the coal plants supplying electricity to California, but owned by non-California firms.
[f] Includes nuclear, biomass, hydropower, wind, geothermal, and solar. They are grouped together because they are treated as having zero emissions.

Table VII. The percentage of electric generating units, California.

	Gas plants[a]		Coal plants[b]		
	Turbines	Boilers	Conventional	CFB	IGCC
1995	25.8	74.2	95.0	5.0	0
2010	27.7[c]	72.3[c]	50.0	35.0	15.0

[a] Derived from CEC's projection.[42]
[b] Our projection.
[c] CEC's 2007 projection.[42]

mix. Nonetheless they estimated that the use of EVs in the Los Angeles area would reduce CO emissions by 99.8 percent. HC emissions by 99 percent, and NO_x emissions by 79 percent, quite similar to our findings. They did not estimate PM and SO_x emission impacts.

Our findings underestimate the emission benefits of EVs for California. First, we include emissions from out-state coal power plants. For example, if emissions of out-state coal plants are excluded, electric automobiles would have 23–87 percent decrease in NO_x, 45–83 percent decrease in SO_x, and 27 percent increase to 18 percent decrease in PM, on a per mile basis, depending on emission control scenarios and two target years. Second, electric vehicles will shift automotive emissions from densely-populated metropolitan areas, where many people are exposed to the pollution, to less-populated areas, where some power plants are located and where fewer people would be exposed. Third, EVs will also shift emissions to the nighttime, because electric vehicles will be recharged mostly during the night, when less people will be exposed.

An important qualification to our findings, as indicated above, is specific mix of fuels used to satisfy the incremental demand for electricity created by use of EVs. We assumed that each increment of additional electricity demanded by EVs would increase power plant emissions by the same proportional increment without EVs; that is, we used state-wide average emission factors. If EVs are recharged primarily in the evening (which probably would be encouraged by pricing favoring recharging during off-peak hours), then incremental emissions may be different from average emissions because base load plants will be in operation. Generally, emissions from base load plants are lower than average, if nuclear or hydropower are the main sources, but may be just as high or higher than average if coal is the base load source.

Also changes in emissions as presented here do not necessarily accurately represent the change in air quality, partly because of spatial considerations, but also because complex chemical processes in the atmosphere convert HC and NO_x emissions into ozone, and SO_x and NO_x emissions into acid rain. Generally, more emissions are worse than less emissions, but sophisticated models are needed to predict ozone and acid rain impacts. As an illustration of the relationship between HC and NO_x emissions and ozone concentrations, note that Hempel et al.[9] ran their emission reductions reviewed above in an ozone photochemical model; with 46.5 percent market penetration by EVs, and including emissions from all other sources, the model projected a 15 percent ozone reduction in the Los Angeles air basin in 2010. In practice, though, ozone (and acid rain) models are highly inaccurate and highly sensitive to detailed emission and meteorological data and ambient air pollution input data which are rarely available in sufficient detail.[47]

The actual air pollution benefits of EVs are limited by the rate and magnitude of EV market penetration. Current EVs, because of the low energy density of batteries, have a shorter driving range than comparable gasoline-powered ICEVs do, although the technology is improving gradually. Given the current EV performance, the most likely initial EV market is believed to be light duty vans.[48] Our analysis does not esti-

Table VIII. EV electricity consumption rate (Kwh/mile, from the outlet).

		1995	2010
High Electricity Consumption	Autos	0.5	0.4
	LDTs	0.9	0.7
Low Electricity Consumption	Autos	0.4	0.3
	LDTs	0.7	0.5

mate emission reductions for EVs which would have the same performance as the replaced ICEVs. Rather, we assume that cost[49] and/or regulatory incentives will allow EVs to replace a portion of the ICEV fleet. In any case, without strong government mandates or incentives, EV market penetration will be slow, and the corresponding air pollution benefits will be small.

Conclusions

The unequivocal conclusion of this paper is that in California and the United States the substitution of EVs for gasoline-powered vehicles will dramatically reduce CO and HC and to a lesser extent, NO_x emissions. The magnitude of NO_x, SO_x, and particulate emission impacts is particularly sensitive to the use of more effective emission control technologies in power plants and the use of cleaner fuels to generate electricity.

In California, EVs would have negligible impacts on particulate and SO_x emissions. In the United States, the use of EVs would result in increases in SO_x and particulate emissions of automobile and LDT fleets, but the effect on aggregate SO_x and PM levels would be minimum.

Acknowledgments

Table IX. Emission impacts of electric automobiles per mile relative to gasoline-powered automobiles, percentage, U.S.

	Minimum impact scenario[a]		Maximum impact scenario[b]	
	1995	2010	1995	2010
HC	−96	−95	−96	−96
CO	−98	−99	−98	−99
NO_x	145	−56	55	−78
SO_x	905	321	517	86
PM	551	153	421	90

[a] The minimum impact scenario is the combination of the less stringent emission controls and the high EV electricity consumption.
[b] The maximum impact scenario is the combination of the more stringent emission controls and low EV electricity consumption.

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