Title
Emission Control Cost-Effectiveness of Alternative-Fuel Vehicles

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Publication Date
1993

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Reprint
UCTC No. 227

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Berkeley, CA 94720

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Emission Control Cost-Effectiveness of Alternative-Fuel Vehicles

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Reprinted from
SAE Technical Paper Series
No. 931841 (1993)

UCTC No. 227

The University of California Transportation Center
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To: Readers of SAE Technical Paper 931841--Emission Control Cost Effectiveness of Alternative Fuel Vehicles

From: Authors of SAE Technical Paper 931841

Re.: **Corrections Made in SAE Technical Paper 931841**

An error in calculating emissions of non-methane hydrocarbon (NMHC) from gasoline vehicles was detected in our paper. Consequently, corrections were made in several occasions. The corrections made are presented below.

(1) Annual emissions of exhaust and evaporative NMHC from gasoline vehicles were corrected (see the attached new Table 13).

(2) Life-cycle emission reductions by alternative fuel vehicles for NMOG-RAF (non-methane organic gases adjusted by ozone reactivity factors), 1,3-butadiene, benzene, formaldehyde, and acetaldehyde were corrected (see the attached new Table 14).

(3) Emission control cost-effectiveness of alternative fuel vehicles was corrected (see the attached new Figures 2-3).

(4) Second paragraph of the Conclusions section (the last paragraph of Column 2 on Page 10): the number of \$26,000 on line 3 was changed to \$36,000; and the number of \$12,000 on Line 4 was changed to \$15,000.

We apologize for the inconvenience that might be caused by these corrections.

Table 13 Emission Rates and Total Emissions of a 1995 Model-Year Gasoline Car

Calendar Year	Emission Rates (grams/mile)[a] NMHC (exh.)[c]	NMHC (evap.)[d]	CO	NO_x	Annual Emissions (pounds/year)[b] NMHC (Exh.)[c]	NMHC (evap.)[d]	CO	NO_x
1995	0.229	0.274	2.623	0.291	6.50	7.79	74.55	8.27
1996	0.289	0.276	4.026	0.376	8.02	7.66	111.73	10.44
1997	0.378	0.281	6.140	0.507	10.23	7.61	166.35	13.74
1998	0.459	0.288	8.087	0.631	12.04	7.55	211.97	16.54
1999	0.535	0.294	9.912	0.748	13.56	7.45	251.07	18.95
2000	0.820	0.330	14.052	1.005	19.87	8.00	340.47	24.35
2001	1.079	0.364	17.825	1.249	25.20	8.50	416.18	29.16
2002	1.317	0.398	21.299	1.480	29.29	8.85	473.83	32.93
2003	1.542	0.432	24.574	1.698	32.60	9.13	519.63	35.90
2004	1.748	0.466	27.595	1.905	35.04	9.34	553.12	38.18
2005	1.926	0.500	30.222	2.103	36.90	9.58	579.14	40.30
2006	2.102	0.535	32.798	2.290	37.96	9.66	592.39	41.36
2007[e]	0.182	0.122	2.620	0.221	3.29	2.20	47.32	3.99
2008[e]	0.242	0.122	4.024	0.305	4.36	2.20	72.68	5.51
2009[e]	0.410	0.126	6.138	0.437	5.95	2.28	110.86	7.89

[a] Calculated with Mobile5A.

[b] Calculated with the grams-per-mile emission rates presented in this table and annual VMT presented in Table 9.

[c] Exhaust NMHC emissions.

[d] Evaporative NMHC emissions. Evaporative emissions here include diurnal, hot soak, running losses, resting losses, and refueling emissions.

[e] A new GV was assumed to be introduced in 2007. Thus, emissions in years 2007-2009 are for this new GV.

Table 14 PV of Life-Cycle Emission Reductions by AFVs (Pounds)[a]

	NMOG-RAF	CO	NO_x	1,3-but	Benzene	Formal	Acetal.
Low-Emission Reduction Scenario							
M85 FFVs	124.0	0.0	0.0	0.48	8.69	7.70	1.10
M100 FFVs	146.5	0.0	0.0	0.49	9.41	6.85	1.14
M85 Dedi. Vehicles	152.6	269.5	0.0	0.50	9.71	6.01	1.18
M100 Dedi. Vehicles	166.9	269.5	0.0	0.52	10.06	5.16	1.21
E85 FFVs	63.1	0.0	0.0	0.48	9.65	1.30	-14.19
LPGVs	177.3	539.0	0.0	0.56	11.58	1.07	0.53
Dual-Fuel CNGVs	215.6	539.0	0.0	0.60	11.84	2.79	0.84
Dedicated CNGVs	218.8	808.5	0.0	0.60	11.87	2.04	0.95
EVs	240.1	2711.7	143.5	0.64	12.46	2.34	1.62
High-Emission Reduction Scenario							
M85 FFVs	436.9	1078.0	19.8	2.01	39.19	24.03	4.70
M100 FFVs	446.7	1078.0	19.8	2.06	40.37	-20.65	4.85
M85 Dedi. Vehicles	538.2	2156.0	19.8	2.16	42.02	-13.88	5.16
M100 Dedi. Vehicles	583.1	3233.9	39.5	2.20	42.74	-10.50	5.32
E85 FFVs	273.4	1078.0	19.8	2.01	42.44	2.69	-46.26
LPGVs	603.8	4311.9	0.0	2.35	45.78	1.74	3.88
Dual-Fuel CNGVs	691.0	4311.9	0.0	2.43	46.38	-2.18	-4.61
Dedicated CNGVs	703.8	5389.9	19.8	2.44	46.52	0.82	-5.01
EVs	761.5	11182.1	205.1	2.57	48.56	10.15	-6.46

[a] PV of AFV life-cycle emission reductions was calculated with baseline GV emissions and AFV emission reduction rates. A positive number means emission decrease, while a negative number means emission decrease.

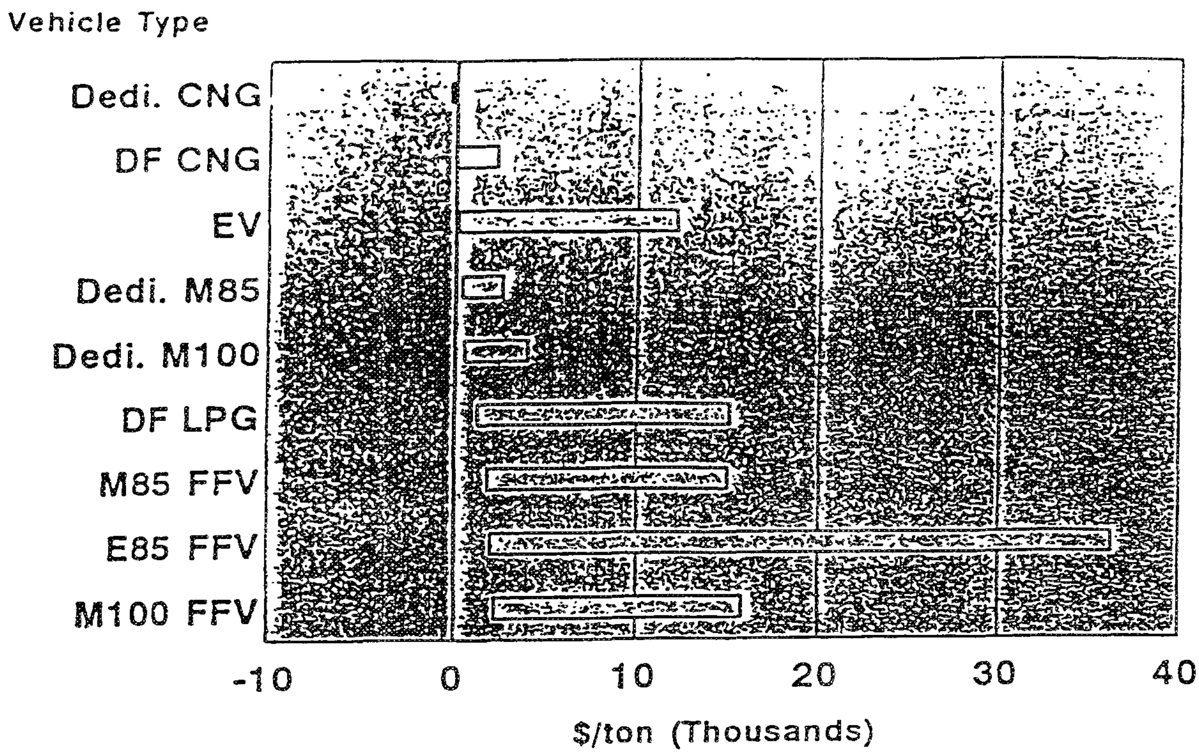

Figure 2 Emission Control Cost-Effectiveness of AFVs, Including Air-Toxic Pollutants

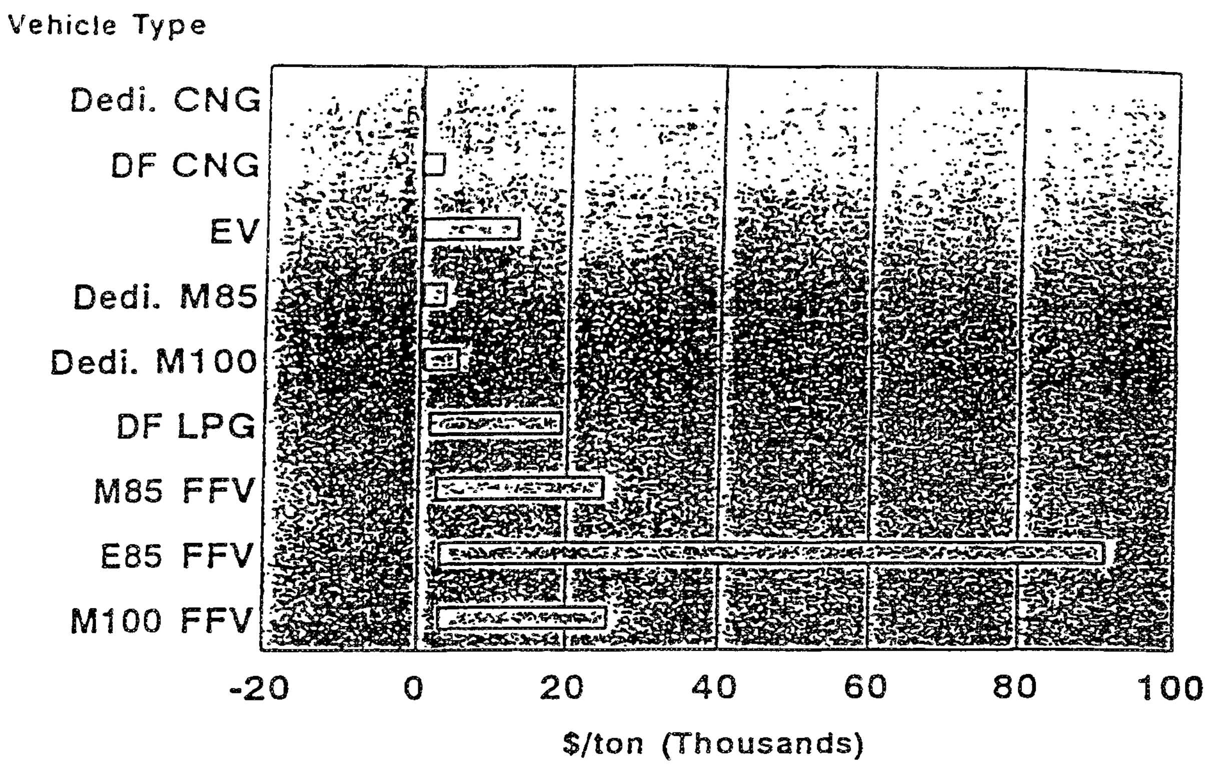

Figure 3 Emission Control Cost-Effectiveness of AFVs, Excluding Air-Toxic Pollutants

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Emission Control Cost-Effectiveness of Alternative-Fuel Vehicles

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ABSTRACT

Although various legislation and regulations have been adopted to promote the use of alternative-fuel vehicles for curbing urban air pollution problems, there is a lack of systematic comparisons of emission control cost-effectiveness among various alternative-fuel vehicle types. In this paper, life-cycle emission reductions and life-cycle costs were estimated for passenger cars fueled with methanol, ethanol, liquified petroleum gas, compressed natural gas, and electricity. Vehicle emission estimates included both exhaust and evaporative emissions for air pollutants of hydrocarbon, carbon monoxide, nitrogen oxides, and air-toxic pollutants of benzene, formaldehyde, 1,3-butadiene, and acetaldehyde. Vehicle life-cycle cost estimates accounted for vehicle purchase prices, vehicle life, fuel costs, and vehicle maintenance costs.

Emission control cost-effectiveness presented in dollars per ton of emission reduction was calculated for each alternative-fuel vehicle type from the estimated vehicle life-cycle emission reductions and costs. Among various alternative-fuel vehicle types, compressed natural gas vehicles are the most cost-effective vehicle type in controlling vehicle emissions. Dedicated methanol vehicles are the next most cost-effective vehicle type. The cost-effectiveness of electric vehicles depends on improvements in electric vehicle battery technology. With low-cost, high-performance batteries, electric vehicles are more cost-effective than methanol, ethanol, and liquified petroleum gas vehicles.

INTRODUCTION

Alternative-fuel vehicles (AFVs) have been promoted to curb urban air pollution. In fact, in many parts of the U.S., AFVs will be required to comply with federal or state air quality standards. Among the AFVs that have been considered are vehicles fueled with methanol, ethanol, liquified petroleum gas (LPG), compressed natural gas (CNG), and electricity. Despite the interest in these AFVs, there have been virtually no systematic comparisons of emission control cost-effectiveness among them. Without such comparisons, the most cost-effective AFV type for controlling air pollution cannot be determined. This paper estimates life-cycle emission reductions and costs of methanol, ethanol, LPG, CNG, and electric vehicles and calculates and compares their emission control cost-effectiveness in dollars per ton of emissions reduced.

PREVIOUS STUDIES

A few past studies have estimated the cost-effectiveness of AFVs. A study by the Office of Technology Assessment (OTA)[1] estimated the cost-effectiveness in dollars per ton of volatile organic compounds (VOCs) control. The study estimated that per-ton VOC control costs ranged from $550 (1990 dollars)* for lowering gasoline vapor pressure to $43,000 for use of methanol vehicles (MVs). In calculating the cost of $43,000 for MVs, the OTA study assumed a reduction rate of 50% for VOC emissions by MVs over comparable gasoline vehicles (GVs), a methanol retail price of $0.93 per gallon (price of $0.67 and federal and state excise taxes of $0.26), and a gasoline price of $1.05 per gallon. The study assumed no incremental cost for MVs relative to GVs, although it acknowledged that an incremental vehicle cost of $500-$1,000 for MVs could increase per-ton control cost by $10,000-$20,000. The study did not present details of its calculation and it implicitly assumed dedicated MVs.

Lareau[2] estimated VOC control costs by MVs under different cases that reflected various factors such as the price differentials between methanol and gasoline, the initial price of

* Costs are presented in 1990 constant dollars throughout this paper. Some previous studies cited here presented costs in current dollars; these are converted into 1990 constant dollars with consumer price index for transportation expenditure.

MVs, operation and maintenance costs of MVs, and VOC emission reductions of MVs. He estimated that per-ton VOC control cost of MVs ranged from as low as $3,000 to as high as $691,000, with the majority of the cost estimates being above $20,000. He concluded that MVs would be desirable only under cost and emission assumptions favorable to them.

Fraas and McGartland[3] calculated hydrocarbon (HC) control costs by M85 (mixture of 85% methanol and 15% gasoline by volume) flexible-fuel vehicles (FFVs), M100 (100% methanol) dedicated vehicles, CNG vehicles (CNGVs), and oxygenated fuels. Taking into account fuel prices, vehicle costs, and emission reductions, the authors estimated per-ton HC control costs of $3,300 to $29,000 for M85 FFVs, negative $3,900 to $7,800 for M100 dedicated vehicles, and negative $9,000 to $170 for CNGVs. They estimated per-ton carbon monoxide (CO) control costs of negative $670 to negative $10 for an oxygenated fuel containing 10% ethanol and 90% gasoline by volume. The wide cost ranges were primarily due to the authors' assumptions regarding fuel prices and AFV emissions reductions.

Krupnick et al.[4] evaluated the cost-effectiveness of M85 FFVs and M85 dedicated vehicles for the target year 2000 and M100 dedicated vehicles for the target year 2010. They estimated a cost of $66,000 per ton of VOC reduction by FFVs, $31,000 by M85 dedicated vehicles ($12,000 under more optimistic assumptions), and $51,000 by M100 dedicated vehicles ($27,000 under more optimistic assumptions). The high cost of M100 dedicated vehicles compared with M85 dedicated vehicles was due to the authors' assumptions of lower emissions of GVs in 2010, the year in which the cost of M100 dedicated vehicles was estimated. They concluded that the replacement of GVs by MVs would be an expensive method of VOC reductions.

The cost estimates by the above-cited studies are summarized in Table 1.

These studies included emission reductions of HC (or VOC) only, even though the use of AFVs certainly affects emissions of other pollutants such as CO, nitrogen oxides (NO_x), and toxic air pollutants. Inclusion of these other pollutants would have led to different magnitudes for AFV cost-effectiveness. In estimating cost-effectiveness, the studies did not include all AFV types; therefore, it is impossible to compare different AFV types within a given study. Comparisons of different AFV types across studies are not appropriate because different assumptions were used in different studies. When estimating HC emission reductions, these studies did not adjust HC emissions according to the differences in the ozone-forming potential by different AFV types, nor did they adjust HC emissions in a precise fashion such that ozone-forming potentials of various HC species were considered. In addition, these studies did not include HC evaporative emissions.

This study included three criteria air pollutants of HC, CO, and NO_x and four air toxic pollutants of 1,3-butadiene, benzene, formaldehyde, and acetaldehyde. Both exhaust emissions and evaporative emissions were considered. AFV emission reductions were estimated from the emission test results of AFVs. Life-cycle emission reductions of AFVs were estimated by considering vehicle life, annual VMT (vehicle miles traveled), and vehicle emission control deterioration over age. HC emissions of different AFV types were adjusted according to HC ozone-forming potentials for different AFV types.

Vehicle life-cycle costs were calculated by accounting for vehicle initial prices, fuel prices, vehicle fuel usage, vehicle maintenance costs, vehicle life, and annual VMT. Life-cycle cost differences between AFVs and GVs, together with life-cycle AFV emission reductions, were used to calculate the life-cycle average emission control cost for each AFV type.

This study included these AFV types: M85 FFVs, M100 FFVs, M85 dedicated vehicles, M100 dedicated vehicles, E85 (mixture of 85% ethanol and 15% gasoline by volume) FFVs, dual-fuel LPG vehicles (LPGVs), dual-fuel CNGVs, dedicated CNGVs, and battery-powered electric vehicles (EVs).

AFV EMISSION CHANGES

TAILPIPE EXHAUST EMISSIONS - AFV emission changes that were estimated in past studies were summarized by Wang et al.[5] Wang et al.'s summary showed wide ranges of AFV emission changes among various studies. These wide ranges were caused by various assumptions regarding baseline GV emissions, AFV technology and design, and the use of AFV emission control systems, among other factors.

Since those studies, a large number of AFVs have been tested for exhaust emissions. This study collected about 200 individual AFV tests recently conducted by the California Air Resources Board (CARB), the U.S. Environmental Protection Agency (EPA), and the Auto/Oil Air Quality Improvement Program (a program funded by the three domestic auto companies and 14 oil companies to study the effects on air quality of using motor alternative fuels and reformulated gasoline). Emission reductions for each individual test were calculated and presented in an AFV emission database. In calculating AFV emission reductions, particular attention was paid to the selection of baseline GVs, the differences in HC emissions measured with different methods, and the differences in HC ozone-forming potentials by different AFV types. These issues are discussed below.

Selection of Baseline GVs - Two options are available for comparing the emissions of flexible-fuel or dual-fuel AFVs with those of GVs. The first option is to compare different fuels used in the same vehicles, the second is to compare AFVs with dedicated GVs. The advantage of the first option is that the vehicles operating on different fuels are exactly the same. The effect of vehicle specifications and emission control systems on emission differences among various fuels can be controlled. The disadvantage of this option is that the same vehicles may not be optimized for a particular fuel.

The second option ensures that optimized GVs are selected because existing GVs are a mature, optimized product of a half-century of vehicle design and production experience. But the option may not ensure that optimized AFVs are selected because flexible-fuel or dual-fuel AFVs may or may not be optimized for operating on alternative fuels. This implies that potential emission reductions of AFVs tend to be underestimated with this option. Therefore, the first option was used to compare emissions of flexible-fuel or dual-fuel AFVs with those of GVs.

Emissions of a dedicated-fuel AFV have to be compared with those of a dedicated GV. Selection of a baseline GV is critical for estimating emission reductions of the dedicated AFV. Emission tests were conducted for some dedicated AFVs together with comparable GVs. For those dedicated AFVs, the tested GVs were selected as the baseline GVs. However, most dedicated AFVs were tested alone. For those, comparable GVs tested by the EPA for emission certification were selected. To eliminate the emission effects of emission control technologies and vehicle specifications and performance, the GVs with emission control technologies, specifications, and performances similar to those of the relevant, dedicated AFVs were selected. Specifically, the following criteria were used to select a baseline GV: same car model, same engine displacement, and same emission control systems between the dedicated AFV and the GV.

Conversion of HC Emissions Measured with Different Methods to NMOG Emissions Measured with Gas Chromatography Method - Vehicle HC emissions are presented in at least three forms in the literature: total hydrocarbon (THC), non-methane hydrocarbon (NMHC), and non-methane organic gas (NMOG). NMOG emissions were used in this study; emissions of HC and NMHC that were presented in some tests were converted into emissions of NMOG.

Some emission tests were conducted with the standard flame ionization detection (FID) method used for measuring GV HC emissions. Because of the under-response rate of the FID method to methanol and the over-response rate to methane, FID-measured NMOG emissions for MVs and CNGVs do not accurately represent actual NMOG emissions. For these tests, the FID-measured NMOG emissions were adjusted to the NMOG emissions measured with the gas chromatography (GC) method -- an accurate method for measuring NMOG emissions from MVs and CNGVs. EQ (1) was used to convert different measurements for MVs and CNGVs into GC-measured NMOG emissions:

$$\begin{aligned} NMOG &= NMHC(GC) + CH_3OH + HCHO \\ &= NMHC(FID) + (1-RF_m) \times CH_3OH + HCHO \\ &= THC(FID) + (1-RF_m) \times CH_3OH - RF_{me} \times CH_4 + HCHO \end{aligned} \quad (1)$$

Where:

NMOG	non-methane organic gas emissions measured with GC method
NMHC(GC)	non-methane hydrocarbon emissions measured with GC method
CH_3OH	methanol emissions measured with GC method
HCHO	formaldehyde emissions measured with high-performance liquid chromatography method
NMHC(FID)	non-methane hydrocarbon emissions measured with FID method
RF_m	methanol response factor of FID (assumed to be 0.8)
RF_{me}	methane response factor of FID (assumed to be 1.26)
CH_4	methane emissions measured with GC method

As EQ (1) indicates, the conversion of different HC measurements into NMOG emissions requires input data of methanol, formaldehyde, methane, and HC emissions. Some tests collected in this study did not contain all of the input items necessary for the conversion. For those tests, NMOG emissions could not be calculated.

The HC emissions from GVs are usually measured as total hydrocarbon emissions. NMHC emissions from GVs were estimated by assuming 80% of total HC emissions as NMHC emissions (the ratio is commonly used for catalyst-equipped GVs). Similarly, it was assumed that 80% of total HC emissions were NMHC emissions for LPGVs. It was further assumed that NMOG emissions were equal to NMHC emissions for GVs, CNGVs, and LPGVs since emissions of alcohols and aldehydes, which contribute to the difference between NMHC and NMOG, are negligible for these vehicles.

Reactivity Adjustment Factors for NMOG - Based on smog chamber experiments, CARB has estimated maximum incremental reactivity (MIR) and maximum ozone reactivity (MOR) in grams of ozone formed per gram of an individual HC species.[6] The MIR and the MOR scales each depict a different set of ozone-forming conditions. The MIR scale is based on atmospheric conditions in which small changes in HC concentrations have large effects on ozone formation. The MOR scale is based on the conditions in which ozone formation is primarily controlled by atmospheric NO_x concentrations. Together, MIR and MOR scales bracket the range of conditions under which HC reactivity should be appropriately defined. To develop a reactivity adjustment factor (RAF) for a fuel-vehicle type, a NMOG emission profile that contains grams-per-mile emissions by each NMOG species is established; pre-determined MIRs or MORs for individual NMOG species are applied to the speciated NMOG profile to determine the total ozone formed per mile; estimated grams-per-mile ozone is divided by grams-per-mile NMOG to derive grams of ozone per gram of NMOG; the derived grams of ozone per gram of NMOG for a given fuel-vehicle type are divided by those for conventional GVs. The ratio is the RAF for the fuel-vehicle type. To reflect the conditions where HC control has the greatest impact on ozone formation, reactivity adjustment factors developed with MIRs by CARB were used here.

The speciated NMOG emission profiles may be affected by emission control technologies as well as by fuel types. CARB intends to develop RAFs by combining fuel types with its adopted low-emission vehicle categories (i.e., transitional low-emission vehicles, low-emission vehicles, and ultra low-emission vehicles). A set of RAFs were assumed in this study based on CARB's proposed and adopted RAFs (Table 2).

Emission Reductions Summary of the 200 Individual AFV Emission Tests - Means, standards deviations, minimum values, and maximum values of emission reductions were calculated for each AFV type from the estimated emission reductions for each of the 200 individual AFV emission tests. Figure 1 (a-d) presents these values for each AFV type.

Figure 1 shows that LPGVs and CNGVs generally have larger emission reductions than MVs, except that NO_x emissions from CNGVs are higher than those from MVs. RAF-adjusted NMOG emissions from all AFV types are lower than those from GVs mainly because of lower RAFs for alternative fuels. The figure shows large standard deviations and wide ranges of emission changes, indicating the large degree of uncertainty involved in AFV emission impacts.

Emission Reductions of Several Best-Designed AFVs - The above section summarizes emission impacts of existing AFVs. Most of them were either prototype or were converted from GVs. That is, these vehicles were not equipped with the most advanced technologies and their emission control might not be optimized. To assess emission impacts of future AFVs, this section selects several AFV models that have the best designs for emission control and compares the emissions of these AFVs with those of comparable GVs. This comparison will demonstrate the potential emission reductions of future AFVs. Table 3 shows the emission comparison between four best-designed AFVs and their counterpart GVs.

Among the four selected AFVs, the M85 dedicated Lumina, the CNG dedicated Ram van, and the dual-fuel CNG Astro van have large emission reductions, but the M85 FFV Spirit increases emissions for all pollutants except RAF-adjusted NMOG. The large percentage increases in emissions by the FFV Spirit are primarily due to the extremely low emissions of the baseline gasoline-powered Acclaim.

The CNG dedicated Dodge Ram van has the greatest emission reductions. The van is designed with more intensive emission controls than the counterpart gasoline B350 van (i.e., special catalyst formulation, more catalyst loading, and engine modification to reduce engine-out NO_x emissions). If compared with emissions of GVs equipped with equivalent emission control systems, the emission reductions of the dedicated CNG van would be smaller.

Scenarios of Future AFV Exhaust Emission Reductions - Emissions of AFVs are affected by the types of emission-control technologies installed, the tradeoffs between emissions and performance, and the tradeoffs in emissions among different pollutants. Installation of certain emission control technologies and the tradeoffs will be influenced significantly by target emissions of AFVs for meeting emission requirements. Emission reductions of future AFVs will be subject to great uncertainty. To deal with this uncertainty, two scenarios of AFV emission reductions were established (Table 4). Note that when establishing these two scenarios, it was implicitly assumed that future GVs will be fueled with reformulated gasoline.

Electric vehicles do not produce emissions themselves but power plants that generate electricity for EVs do. Wang et al.[16] have estimated per-mile EV emission reductions. EVs could reduce HC and CO emissions by over 95%. EV NO_x emission reductions depend on the type of power plants and NO_x emission-control technologies installed in power plants. Wang et al. projected that with future power plant emission-control technologies, EVs could reduce NO_x emissions by 60-80%. Based on that study, emission reduction rates of 97% for NMOG, 97% for CO, and 70% for NO_x were assumed for the low-emission reduction scenario. Since emissions from up-stream fuel production and distribution were not taken into account for other vehicle types, under the high-emission reduction scenario, power plant emissions were not taken into account for EVs. Therefore, EVs were assumed to achieve 100% of emission reductions under the high-emission reduction scenario.

EVAPORATIVE EMISSIONS - Methanol FFVs generally produce more evaporative emissions when fueled with low-methanol-content blends (i.e., M10 to M50) than when fueled with gasoline or high-methanol-content blends (i.e., M85 to M100). This is because low-methanol-content blends are more volatile than gasoline or high-methanol-content blends.

Although extensive exhaust emission tests have been conducted for MVs, only limited evaporative emission tests have been conducted for them. Auto/Oil studies[10,13] show that, while FFVs reduce diurnal evaporative emissions, they increase hot-soak and running loss evaporative emissions. The studies indicate that dedicated MVs have much lower evaporative emissions than FFVs.

Evaporative emissions from ethanol vehicles operating on E85 were not available. Consequently, it was assumed here that evaporative emissions from ethanol vehicles would be the same as those from methanol vehicles.

Liquified petroleum for vehicles evaporative emissions are negligible, except if LPG is leaked from on-board LPG storage and distribution systems. It was assumed that evaporative emissions from LPG vehicles would be zero.

Compressed natural gas vehicles do not produce evaporative emissions. Even if natural gas is leaked from on-board storage and distribution systems, the leaked natural gas would primarily be methane, which is not an urban air pollution concern because of its extremely low ozone-forming potential (however, methane is a greenhouse gas contributing to potential global warming). Therefore, zero evaporative emissions were assumed for CNGVs.

With the above information, two scenarios of AFV evaporative emission reductions were assumed (Table 5).

AIR-TOXIC EMISSIONS - Four air-toxic pollutants were included in this study: benzene, 1,3-butadiene, formaldehyde, and acetaldehyde. CARB has measured speciated organic gases of NMOG exhaust emissions for various alternative-fuel types. Table 6 summarizes the weight distributions of the four air-toxic pollutants in NMOG exhaust emissions for different vehicle types.

There are no air-toxic evaporative emissions from LPGVs, CNGVs, and EVs and there is virtually no presence of 1,3-butadiene, formaldehyde, and acetaldehyde in evaporative emissions from GVs, MVs, and ethanol vehicles. Thus, evaporative emission changes by MVs and ethanol vehicles were calculated for benzene only. With the information contained in the EPA's air-toxic study,[8] Benzene was estimated to account for 0.643% of evaporative emissions from GVs by weight. Gabele[17] estimated that benzene accounted for 2% of the evaporative emissions from methanol FFVs when fueled with M85 and 1.5% when fueled with M100. Gabele's results for MVs were adopted here. There was no information available regarding the benzene content in E85 FFV evaporative emissions. Consequently, it was assumed that E85 FFVs had the same benzene weight fraction as M85 FFVs did. This is a reasonable assumption because of the similarity between methanol and ethanol vehicles and the relative similarity between methanol and ethanol.

The emission reductions for each air-toxic pollutant for a given AFV type were calculated from the weight percentages of the air-toxic pollutants and NMOG emission reductions of the AFV type. Specifically, EQ (2) below was used to calculate the emission reduction of a given air toxic pollutant for a given vehicle type.

$$EC_{afvi,p} = [(1+EC_{afvi,NMOG}) \times Ratio_{afvi,p} - Ratio_{gv,p}]/Ratio_{gv,p} \qquad (2)$$

Where:

$EC_{afvi,p}$	emission change of air-toxic p by AFV type i (emission reduction is negative and emission increase is positive)
$EC_{afvi,NMOG}$	emission change of NMOG by AFV type i (Tables 4-5, emission reduction is negative and emission increase is positive)
$Ratio_{afvi,p}$	ratio of air-toxic p to NMOG for AFV type i (Table 6)
$Ratio_{gv,p}$	ratio of air-toxic p to NMOG for GVs (Table 6)

Table 7 presents the calculated emission changes of air-toxic pollutants by AFV type. All AFV types reduce benzene exhaust emissions by over 80% and 1,3-butadiene by over 75%. Formaldehyde emissions are increased by the use of AFVs: MVs increase formaldehyde emissions by 200-300%, CNGVs and LPGVs by about 100%, and ethanol vehicles by 50%. However, the use of EVs reduces formaldehyde emissions. EVs eliminate acetaldehyde emissions, MVs reduce acetaldehyde emissions by over 70%, CNGVs reduce acetaldehyde emissions by over 55%, and LPGVs change acetaldehyde emissions very little. However, ethanol vehicles increase acetaldehyde emissions by more than 900%. Both methanol and ethanol vehicles increase evaporative benzene emissions.

LIFE-CYCLE COST DIFFERENCES BETWEEN AFVS AND GVS

MODEL OF CALCULATING VEHICLE LIFE-CYCLE COSTS - A model to calculate life-cycle costs of GVs and AFVs was established in this study. The model takes into account initial vehicle purchase prices, the annual expenditure on fuels, vehicle maintenance costs, vehicle life, and the cost of inspection and maintenance (I/M) programs. These items are most likely to be different between AFVs and GVs. The cost items that will be similar between AFVs and GVs were not accounted, because such items do not contribute to AFV cost changes. The cost differences were treated as AFV emission control costs.

To take into account the value difference of the costs occurring in different years, the present value (PV) of the life-cycle cost changes was calculated by discounting future costs to present costs (EQ (3)).

$$PV_{cost} = DP + \sum_{i=1}^{n} [(MP_i + FC_i + MC_i + Misc_i)/(1+r)^i] \qquad (3)$$

Where:

PV_{cost}	PV of vehicle life-cycle cost
DP	downpayment on an auto loan
i	vehicle age
n	vehicle life (years)
MP_i	annual total of monthly payments on an auto loan
FC_i	annual fuel cost (calculated from fuel prices, vehicle fuel economy, and annual VMT)
MC_i	annual maintenance cost
$Misc_i$	annual miscellaneous cost (such as cost of vehicle I/M tests)
r	discount rate (a real-term discount rate of 6% was used)

In calculating vehicle life-cycles, 1995 model-year vehicle projections were used. All cost items are presented as the costs to consumers in 1990 constant dollars.

VEHICLE LIFE BY VEHICLE TYPE - A life of 12 years was assumed for baseline GVs. The same lifetime was assumed for MVs, LPGVs, and ethanol vehicles, because these AFV types use liquid fuels and would probably have engine deterioration similar to that of GVs. A lifetime of 13 years was assumed for CNGVs, for gaseous natural gas is predicted to cause less damage to CNG engines. A lifetime of 15 years was assumed for EVs because electric motors are predicted to be more durable than internal combustion engines.

VEHICLE INITIAL PRICES - Incremental prices of AFVs are a major cost component in determining AFV life-cycle costs. Price increases for AFVs are due to the use of various components in AFVs. Methanol FFVs are equipped with fuel sensors that identify the type of fuel coming to the engines. FFV fuel storage and distribution systems need to be modified for material compatibility with methanol. Dedicated methanol vehicles do not need fuel sensors -- the most expensive item used in FFVs. The incremental cost of dedicated methanol vehicles will be negligible. Technologies for ethanol FFVs are similar to those for methanol FFVs.

Most current LPGVs are converted from GVs, although manufacturers are capable of producing OEM (original equipment manufacturer) LPGVs. The conversion of a GV into a dual-fuel LPGV involves installing LPG storage tanks, fuel switches, vaporizers (or regulators), and gas/air mixers. Among these components, LPG storage tanks are the most expensive item. LPGV fuel delivery systems also need to be modified to accommodate LPG delivery.

Dual-fuel CNGVs can be converted from GVs or OEM produced. Among the needed items for dual-fuel CNGVs, storage cylinders (capable of containing CNG at pressures of 2,400-3,000 psi) are the most expensive item. Other items include high-pressure fuel lines to connect the cylinders to CNG fuel metering systems, pressure regulators to reduce gas pressure from its storage pressure to near atmospheric pressure before mixing with air, and fuel selection switches to allow change from one fuel to another. Most components used in dual-fuel CNGVs are necessary for dedicated CNGVs, but gasoline fuel components (such as fuel pumps and gasoline tanks) can be eliminated, reducing the cost of dedicated CNGVs.

The most expensive cost item for EVs is batteries. Since EV batteries need to be replaced intermittently, the calculation of life-cycle cost for EVs is different from that for internal combustion engine vehicles. The EV life-cycle cost calculation is presented in a separate section.

Wang et al.[5] summarized incremental costs of various AFV types estimated by past studies. Based on the cost information presented by them, two vehicle cost scenarios were assumed (Table 8). Note that the price increases here are consistently higher than those estimated in most past studies. This is because the costs presented here are in retail prices, while the costs presented in other studies are usually manufacturing costs.

To estimate prices of AFVs, a baseline gasoline subcompact car was assumed with a retail price of $14,000. In estimating out-of-pocket costs to consumers to purchase a new vehicle, a sales tax rate of 7% was applied to vehicle initial prices.

DOWNPAYMENT (DP) AND ANNUAL TOTAL OF MONTHLY PAYMENTS (MP_i) ON VEHICLE PURCHASE LOANS - About 70% of all new cars are purchased with auto loans.[18] It was assumed here that vehicles would be purchased with auto loans. DeLuchi estimated that downpayments cover about 11% of the loan. His estimate was used here to calculate downpayments. In addition, an annual interest rate of 8% and a loan period of 60 months (5 years) were assumed.

The 12 monthly payments occurring in a year were added together as the annual payments for the year. Because of the standard method of figuring out monthly payments, the calculated yearly payments are in current dollars. An annual inflation rate of 4.18% was used to convert current dollars into 1990 constant dollars. This inflation rate was estimated from the consumer price index of new car expenditures in the last 20 years.

ANNUAL FUEL COSTS (FC_i) - Annual fuel cost is determined by annual VMT, vehicle fuel economy, and fuel prices.

<u>Annual VMT</u> - Annual VMT varies with vehicle age. Table 9 shows the annual VMT of GVs. Because of differences in vehicle performance, fuel cost, and vehicle attributes among different AFV types, these vehicle types will probably be used for different purposes, and thus will have different annual VMTs. However, there are no quantitative data on annual VMT by AFV type. The same annual VMT schedule with vehicle age was assumed here for all vehicle types.

<u>Vehicle Fuel Economy</u> - A fuel economy of 30 miles per gallon (MPG) was assumed for the baseline gasoline car. The fuel economy of MVs can be improved by increasing the engine compression ratio to take advantage of methanol's high octane number. It was assumed here that methanol FFVs would obtain a 5% improvement in fuel economy over GVs on an energy equivalent basis, and that dedicated MVs would obtain a 15% improvement. Similarly, it was assumed that ethanol FFVs would obtain a 5% improvement.

CNGVs can have higher fuel economy than GVs because of natural gas' high octane number and the potential of using a lean-burn strategy in CNG engines. Previous studies have indicated a potential fuel economy improvement as high as 30% for CNGVs, mainly from use of a lean-burn strategy. However, in practice, a lean-burn strategy makes it difficult for CNGVs to meet NO_x emission standards, and thus the strategy may not be used in CNGV designs. Without using a lean-burn strategy, fuel economy improvement by CNGVs is limited. It was assumed here that the lean-burn strategy would not be used in CNGVs. No fuel economy improvement was assumed for dual-fuel CNGVs, and a 5% improvement was assumed for dedicated CNGVs. The improvement in fuel economy by LPGVs is probably similar to that by CNGVs. Thus, no fuel economy improvement was assumed for dual-fuel LPGVs.

EV fuel economy in miles per kwh of electricity is determined by EV powertrain efficiency, electric motor efficiency, battery efficiency, charger efficiency, and efficiency penalty of extra EV weight. EV battery technology which determines both battery efficiency and the extra EV weight is the most important factor in determining EV fuel economy. Wang and DeLuchi[20] developed a model to predict EV fuel economy with different EV battery technologies. EV fuel economy for two battery technology scenarios is predicted in a section below.

PRICES OF ALTERNATIVE FUELS - The prices of motor vehicle fuels are determined by costs of primary energy sources (i.e., crude oil, natural gas, etc.), costs of transporting these sources, costs of producing fuels from primary energy sources, costs of transporting fuels, cost and profit markups in retail stations, and federal and state road excise taxes.

It is commonly assumed that methanol will be produced from natural gas. Thus, price estimates for methanol depend on assumptions regarding price of natural gas feedstock, cost of methanol production, methanol transportation costs, service station costs, and profit markups. Most past studies assumed one of the two general scenarios regarding sites of natural gas production and methanol plants. The first scenario assumed that methanol was produced in remote areas such as the Middle East where natural gas is cheap. The second scenario assumed that natural gas was produced in North America (i.e., the U.S., Canada, or Mexico), is transported through pipelines to U.S., and is converted to methanol. The methanol price estimated under the second scenario is usually higher than that estimated under the first, mainly because of the higher natural gas prices in North America.

CNG price depends on price of natural gas feedstock, natural gas transportation cost, and cost of compressing natural gas. Most CNG cost studies assumed that natural gas was produced in North America, and transported to CNG refueling stations through pipelines. A few studies assumed that natural gas was produced and liquified in remote foreign countries and transported into the U.S. Except for transportation costs in the case of remote foreign natural gas supply, natural gas price and compression cost are the two largest cost components of CNG price. Cost estimates of natural gas compression depend on the types of refueling technologies adopted, for example, fast-filling vs. slow-filling and public refueling stations vs. private home refueling.

Ethanol can be produced from corn, sugarcane, or other biomass through fermentation processes. In the U.S., the primary interest in ethanol fuel is due to its potential use of domestically produced corn, although the cost of ethanol from corn are relatively high. To offset the high cost, the U.S. currently exempts ethanol from the federal road excise tax, and further provides a blender's income tax credit equivalent to $0.60 per gallon of ethanol.

About 60% of U.S. LPG is produced in natural gas processing plants where propane, butane, and other natural gas liquids are separated from natural gas. The remaining 40% is produced in crude oil refinery plants.[21] An LPG distribution system with about 70,000 miles of pipelines currently exists in the U.S.[22] However, most existing LPG outlets are located in industrial outskirts of metropolitan areas and are not designed for private automobiles. The wholesale price of LPG at loading racks currently is about $0.4 per gallon. The transportation cost and profit markups from loading racks to service stations could add another $0.3 per gallon to LPG prices.[23] As the demand for LPG increases in the future because of use of LPGVs, the LPG wholesale price will probably increase. However, as demand increases, LPG transportation costs and per-gallon profit markup will decrease because of the economy of scale. Thus, future LPG retail prices may be comparable to current LPG retail prices.[23]

Electricity prices for EV recharging could be varied with time of day. Past EV studies usually assumed off-peak, nighttime EV recharging with some EV opportunity recharging during the day. Electricity prices for off-peak recharging have been assumed lower than average electricity prices.

Past studies of estimating prices of alternative fuels were summarized by Wang et al.[5] Generally, on an energy-equivalent basis, methanol and ethanol are more expensive than gasoline, while CNG and LPG are less expensive. Because of the complexity of predicting the prices of different fuels, no effort was made to predict fuel prices in this paper. There are wide ranges in alternative fuel price estimates. The wide ranges result from the assumptions made regarding prices of primary energy sources (i.e., natural gas and corn), costs of fuel production, distribution, and refueling station markups. To deal with the uncertainty of future fuel prices, two scenarios of fuel prices were established on the basis of past price estimates (Table 10).

Fuel prices will probably change between 1995 and 2009. This period is used to approximate the life of an EV, which is predicted to have the longest lifetime of all AFVs. On the one hand, the depletion of primary energy sources may lead to increases in fuel prices. On the other hand, the improvement in production technology and increase in production scale may lead to decreases in alternative fuel prices. The net results are unknown. It was assumed in this study that real-term prices of all fuels would be constant between 1995 and 2009.

OTHER COST ITEMS - Some other costs items are presented below.

Vehicle Maintenance Costs - The scheduled and unscheduled maintenance costs of GVs estimated by The Federal Highway Administration (FHWA) were used as the baseline maintenance costs (Table 9). The same maintenance costs were assumed for GVs, MVs, ethanol vehicles, LPGVs, and CNGVs. These vehicles are internal combustion engine vehicles and will be probably subject to similar maintenance requirements.

EVs are driven by electric motors which are more reliable than internal combustion engines. EVs do not require oil changes. Electric motors and electric systems for EVs require less intensive maintenance. Because of these, EV maintenance cost should be lower than that of internal combustion engine vehicles. EV maintenance costs were assumed to be 60% of those of internal combustion engine vehicles.

Cost of I/M Programs - I/M programs are implemented in ozone and CO non-attainment areas to ensure that vehicles are properly maintained for lower in-use vehicle emissions. Currently, 35 states implement I/M programs. Among them, 7 states have bi-annual I/M programs, and the remaining 28 states have annual I/M programs.

Current I/M programs require I/M tests to be conducted with vehicles in idle mode. In California, the idling I/M test may cost vehicle owners about $30 (including $7 for issuing an I/M certificate). The EPA has recently adopted an enhanced I/M program that will be implemented in serious, severe, and extreme ozone non-attainment areas.[27] The enhanced I/M program requires vehicles to be tested as they are driven on dynamometers. Due to the added complexity, the cost of the enhanced I/M program will be high. The cost of the enhanced I/M program was assumed to be $40 per test. The EPA states that due to the effectiveness of the enhanced I/M program, the annual I/M programs that are currently implemented in most states can be replaced by bi-annual programs. Therefore, a bi-annual I/M program was assumed in this study.

Since GVs, MVs, ethanol vehicles, LPGVs, and CNGVs produce emissions, these vehicles will be subject to the I/M requirement. Therefore, the I/M cost was applied to these vehicles. On the other hand, since EVs do not produce emissions themselves, they will not be subject to the I/M requirement, and therefore no I/M cost was applied to EVs.

EV COST ITEMS - Assumptions regarding EV cost items are presented in this section.

EV Price Without Battery - Electric motors, on-board electric controllers, and powertrains for EVs are less complex than the counterparts for internal combustion engine vehicles. As a result, the cost of EVs, when EV batteries are excluded, would be lower than the cost of GVs. The prices of EVs without batteries were assumed here to be 80% of the price of GVs.

Battery Costs - Battery costs are determined primarily by battery technology. The U.S. Advanced Battery Consortium (USABC), a consortium sponsored by vehicle manufacturers, electric utility companies, and the U.S. Department of Energy, has established mid-term and long-term goals for battery performance and cost. A low-cost and a high-cost scenario were established in this study for battery costs and performance. The low-cost scenario reflects USABC's long-term battery goals, while the high-cost scenario reflects the USABC's mid-term battery goals. Table 11 presents battery performance attributes and costs for each scenario. EVs equipped with the mid-term battery need one replacement for every 63,750 miles at a cost of $9,375 for each replacement, and EVs equipped with the long-term battery do not need any battery replacement during the their life.

Cost of Home Recharge Systems - DeLuchi[18] estimated a cost of $300 to upgrade the electric system at a private home to accommodate EV recharging needs. The home recharge system can last as long as a home lasts. However, to calculate the annual cost of the home recharging system, he assumed 30 year lifetime--the standard term for home loans. Using an interest rate of 10% for home loans, an annual cost of $32 was calculated for a home recharging system.*

RESULTS OF AFV LIFE-CYCLE COST DIFFERENCES - Based on the above calculations and assumptions, life-cycle costs of AFVs were calculated relative to GVs. Table 12 presents the calculating results. Life-cycle costs of most AFV types are higher than those for GVs. The cost increases for MVs and ethanol vehicles are due to their high purchase prices and the increase in per-mile fuel cost. The large cost increase for ethanol vehicles between the low-cost scenario and the high-cost scenario is due to the large increase in ethanol price between the two scenarios. The cost increase for LPGVs results from the need to install on-board LPG storage tanks and from the increase in per-mile fuel cost. CNGV costs are lower because the cost of on-board CNG storage cylinders is offset by lower per-mile fuel cost. The largest increase in vehicle life-cycle costs occurs in EVs under the high-cost scenario, which is due primarily to the high EV battery cost. Under the low cost scenario, EV costs are reduced greatly. This indicates that the development of high-performance, low-cost EV batteries is essential for successful introduction of EVs.

EMISSION CONTROL COST-EFFECTIVENESS OF AFVS

EMISSIONS OF BASELINE GVS - Emissions of GVs increase as they become old. To account for emission control deterioration over vehicle age, emission rates in grams per mile were estimated for each calendar year during the life of a GV. And then, the estimated grams-per-mile emission rates were multiplied with annual VMT for each year to calculate total emissions for each year.

EPA's Mobile5A was used to estimate grams per mile emission rates by calendar year for a 1995 baseline GV. The input program for Mobile5A designed here included an enhanced I/M program with transient emission testing, application of Tier-I emission standards to 1995 model-year vehicles, and use of Stage II refueling evaporative emissions in gasoline service stations. In addition, ambient temperature and gasoline vapor pressure of Los Angeles were assumed in

* The calculated annual cost of $32 is in current dollars. The current dollars were converted into 1990 constant dollars with an annual inflation rate of 6.39%. This inflation rate was calculated from the consumer price index for housing expenditures over the last 20 years.

Mobile5A. Table 13 presents the calculated annual emission rates in grams per mile and annual emissions in pounds.

Using the calculated pounds per year emissions, the present value (PV) of GV emissions was calculated over 12-, 13-, and 15-year periods, since emission reductions were calculated for MVs, LPGVs, and ethanol vehicles over the 12-year period, CNGVs over the 13-year period, and EVs over the 15-year period. PV of total emissions rather than the straight sum of annual emissions was calculated because PV of costs for AFVs was calculated. In calculating PV of emissions, a discount rate of 6% was used. This is the same rate used in calculating PV of AFV costs.

Recent tunnel and remote sensing studies of actual on-road motor vehicle emissions have indicated that emission estimating models such as Mobile5A underestimate actual emissions.[29-30] The National Research Council[31] concluded that on-road vehicle HC and CO exhaust emissions might be 2-4 times more than emissions estimated by models. In calculating AFV emission reductions for the high-emission reduction scenario, actual on-road HC and CO exhaust emissions of GVs were assumed to be 3 times more than the estimated emissions with Mobile5A. Since exhaust air-toxic pollutants are contained in HC emissions, actual on-road air toxic exhaust emissions of GVs were assumed to be three times more than the estimated air-toxic exhaust emissions as well.

LIFE-CYCLE EMISSION REDUCTIONS BY AFVS - With the calculated life-cycle emissions of baseline GVs and emission reduction rates for AFVs assumed under the two AFV emission reduction scenarios, life-cycle emission reductions were calculated for each AFV type* (Table 14). Because a new GV with low emissions was introduced in year 13, a 13-year old CNGV may not have emission reductions relative to the new GV. It was assumed that there were no emission reductions for CNGVs in year 13. For EVs, the emission reduction rates applied to the first 12 years were applied to years 13-15.

COST-EFFECTIVENESS OF EMISSION REDUCTIONS BY AFV TYPES - For calculating AFV cost-effectiveness in dollars per ton of emissions controlled, a composite tonnage of emission reductions was calculated from emission reductions of the seven pollutants. To do so, the damage value of each pollutant was used as the weighing factor. A factor of one was assigned to NMOG emissions, and weighing factors of other pollutants were calculated relative to that of NMOG.

To calculate weighing factors of CO and NO_x, the damage value in dollars per ton for each of the three pollutants was used. The four air-toxic pollutants are classified as carcinogens, and the most damaging effect is their resultant cancer incidence. The cancer risk per unit of concentration for each air-toxic pollutant was used to calculate relative weighing factors among the four pollutants. Then, assuming that benzene was nine times more damaging than NMOG, weighing factors of the four air-toxic pollutants were calculated relative to NMOG. Table 15 presents the information that was used to calculate relative weighing factors, and the resultant weighing factors.

With the estimated life-cycle cost changes and the composite tonnage of emission reductions of AFVs relative to those of GVs, cost-effectiveness was calculated in dollars per ton of emission reduction. Specifically, EQ (4) below was used to calculate emission control cost-effectiveness for each AFV type.

$$ECCF_{afvi,\,j,\,k} = (LFCost_{afvi,\,j})/(LFTonnage_{afvi,\,k}) \quad (4)$$

Where

$ECCF_{afvi,\,j,\,k}$ emission control cost effectiveness for AFV type i under cost scenario j and emission reduction scenario k ($/ton)

$LFCost_{afvi,\,j}$ life-cycle cost difference between AFV type i and GVs under cost scenario j (Table 12)

$LFTonnage_{afvi,\,k}$ reduction in life-cycle composite emission tonnage by AFV type i under emission reduction scenario k (emission reductions for the composite tonnage of seven pollutants were calculated as described above, emission reductions under two emission reduction scenarios were presented in Table 14)

Figure 2 shows emission control cost-effectiveness by each AFV type. Note that for each AFV type, the high value represents the combination of the low-emission reduction and the high-cost scenario, while the low value represents the combination of the high-emission reduction and the low-cost scenario.

Several conclusions can be drawn from Figure 2. First, among all vehicle types, dedicated CNGVs, dual-fuel CNGVs, and dedicated MVs (both M85 and M100) have the lowest dollar per ton control costs, primarily because of the large emission reductions and low fuel costs of CNGVs, and because of lower vehicle costs for dedicated MVs. In fact, use of CNGVs leads to cost savings. Second, there is a wide range of cost-effectiveness for EVs, LPGVs, and FFVs. The wide range is mainly caused by differences in the low-cost and the high-cost scenario assumptions. Third, FFVs have much higher control costs than dedicated vehicles because of lower

* By using life-time GV emissions and AFV emission reduction rates, it was assumed here that both zero-mile emissions and emission control deteriorations of AFVs were reduced at the AFV emission reduction rates. However, some previous tests showed poor emission control deteriorations of MVs and CNGVs, due to less durable emission control systems used. Durability of emission control systems for these vehicles still needs to be improved.

emission reductions and higher costs of FFVs than those of dedicated vehicles. Fourth, in the low-cost scenario, ethanol FFVs and dual-fuel LPGVs have dollar per ton control costs comparable to those of methanol FFVs, but in the high-cost scenario, ethanol FFVs and dual-fuel LPGVs have much higher control costs than methanol FFVs. Finally, given the low-cost scenario, EVs are more cost-effective than any other AFV types except CNGVs. Given the high-cost scenario, EVs are more cost-effective than E85 FFVs and LPGVs, and have costs comparable to methanol FFVs.

To demonstrate the effect of air-toxic emission reductions on AFV cost-effectiveness, AFV cost-effectiveness was calculated by excluding emission reductions of the four air toxic pollutants (Figure 3). The calculated results showed that when air-toxic emission reductions were excluded, dollar per ton control costs increase slightly for each AFV type except ethanol FFVs. Control costs for ethanol FFVs increase considerably. Nevertheless, the ranking of cost-effectiveness among these AFV types remained essentially same.

DISCUSSION

The estimated AFV emission control cost-effectiveness includes AFV emission reduction benefits only. AFVs may have other benefits such as reductions in CO_2 emissions and increases in energy security achieved by diversifying energy sources for the transportation sector. DeLuchi[34] estimated emissions of greenhouse gases from various AFV types. Generally, when compared with GV greenhouse gas emissions, MVs with natural gas as the primary energy source and ethanol vehicles with corn as the primary energy source have comparable levels of greenhouse emissions. LPGVs have lower greenhouse emissions. CNGVs have slightly lower greenhouse gas emissions. EVs with the U.S. electric generation mix have slightly lower greenhouse emissions. When nuclear power, hydro-power, solar power, or wood are used to generate electricity for EVs, EVs have substantial reductions in greenhouse emissions.

The U.S. transportation sector currently relies completely on oil. Of the total U.S. oil consumption (half of which is imported), the transportation sector accounts for two-thirds. As a result, the U.S. transportation sector is vulnerable to disruptions in the world oil market. The use of AFVs will help diversify energy supply sources for the transportation sector and will consequently increase energy security. The use of domestically produced energy for AFVs may reduce energy imports, and therefore reduce the U.S. trade deficit.

The cost-effectiveness calculation is based on the reduction of one ton of emissions from the current GV emission level. The calculation, however, does not address the potential magnitude of emission reductions by each AFV type. By nature, internal combustion engine AFVs cannot eliminate vehicular emissions. In fact, as emissions from these AFV types are reduced further, per-ton emission control costs will increase. On the other hand, EVs have zero vehicular emissions. Emissions attributable to EV use occur in power plants which are generally located outside major urban areas. Therefore, among all the AFV types included in this study, EVs have the greatest potential to reduce emissions in urban areas. EVs potentially could play an important role in helping to curb air pollution in major urban areas. Despite this fact, the cost effectiveness estimate here shows that EVs may not be the most cost-effective vehicle type, demonstrating the cost-effectiveness method's caveat of not indicating the amount of emission reductions for a given cost.

The estimate in this study indicates that dedicated M100 and EVs could be effective in reducing air pollution. However, technologies for these two vehicle types are still relatively new. Dedicated M100 vehicles are difficult to start in cold temperatures and the invisible flame of M100 creates a safety concern. EV technology, especially EV battery technology, also needs to be improved. The mid-term goal and the long-term goal established by the USABC were used for battery cost and performance in the EV cost estimates. Though existing sodium/sulfur battery meets the mid-term goal, no battery has yet been developed which meets the long-term cost and performance goal. Use of batteries such as lead/acid batteries that have high costs and short life cycles would increase the dollar per ton control costs of EVs substantially. Development of low-cost, high-performance batteries is essential for realizing the emission reduction benefits of EVs.

The comparison of emission control cost-effectiveness among different AFV types does not take into account differences in vehicle performance and other vehicle attributes. For example, AFVs likely will have driving ranges shorter than GVs, and EVs probably will be less powerful than GVs. These factors will certainly limit the size of the AFV market; however, after AFVs are purchased, vehicle performance and other attributes become irrelevant in calculating AFV cost-effectiveness.

CONCLUSIONS

The estimates of emission control cost-effectiveness for nine AFV types show that CNGVs are the most cost-effective vehicle type in controlling three criteria air pollutants and four air-toxic pollutants. Dedicated MVs are the next most cost effective vehicle type. The cost-effectiveness of EVs depends on improvements in EV battery technology. With low-cost, high-performance batteries, EVs are more cost-effective than other AFVs, except CNGVs.

The estimates of dollar per ton emission control costs for AFVs show that control costs range from as little as zero to as much as $26,000. Most AFV types have control costs less than $12,000, much below the $25,000 to $40,000 control costs for the five expensive control measures that have been adopted by South Coast Air Quality Management District.[35]

ACKNOWLEDGMENTS

The authors thank the California Institute for Energy Efficiency for providing funding for this study. The authors are grateful to their colleagues Mark DeLuchi, Catherine Kling, and Jonathan Rubin for their helpful discussions during the course of this study. This work was not funded through Argonne National Laboratory.

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Table 1 Summary of AFV Emission Control Cost-Effectiveness

Study	Vehicle Type	Control Cost ($/ton)	Remark
OTA	M100 dedicated	43,000	VOC control
Lareau	Methanol vehicles	3,000 - 691,000	VOC control
Fraas et al.	M85 FFVs	3,300 - 29,000	HC control
	M100 dedicated	-3,900 - 7,800	HC control
	CNG vehicles	-9,000 - 170	HC control
	Oxygenated fuel	-670 - -10	CO control
Krupnick et al.	M85 FFVs	66,000	VOC control in year 2000
	M85 dedicated	12,000 - 31,000	VOC control in year 2000
	M100 dedicated	27,000 - 51,000	VOC control in year 2010

Table 2 Assumed RAFs for AFVs (Based on MIRs of HC Species)

Fuel Type	RAF
Conventional Gasoline	1.00
Reformulated Gasoline	0.98[a]
M85	0.41[b]
M100	0.37[c]
E85	0.63[d]
LPG	0.50[e]
CNG	0.18[f]
Electricity	1.13[g]

[a] Adopted by CARB for transitional low-emission vehicles fueled with California's phase 2 gasoline.

[b] Adopted by CARB for transitional low-emission vehicles fueled with M85.

[c] CARB did not proposed an RAF for M100. CARB's tests indicate that M100 usually has lower ozone-forming potential. It was assumed that RAF for M100 was 90% of that for M85.

[d] Estimated by CARB.[7]

[e] Proposed by CARB for transitional low-emission vehicles fueled with LPG.

[f] Proposed by CARB for transitional low-emission vehicles fueled with CNG.

[g] The RAF for electricity was calculated in this study with data on speciated VOC emissions of power plants and the ozone-forming potential of each species. Weight distribution of VOC species for coal-, natural gas-, and oil-fired power plants were from EPA's VOC speciation database.[8] Ozone-forming potentials were from CARB-estimated ozone-forming potentials of HC species emitted by motor vehicles.[7] With these data, grams of ozone formed for each gram of VOC were calculated as 3.35 for residual oil combustion boilers, 0.886 for natural gas combustion boilers, 2.15 for natural gas turbines, and 4.83 for coal combustion boilers. To calculate average ozone-forming potential of VOC for the U.S. electric generation system, fossil-fuel electric power plant mix of 69.2%, 7.7%, and 23.1% for coal-fired plants, oil-fired plants, and natural gas-fired plants was used.[9] It was further assumed that 80% of natural gas-fired plants are combustion boilers, and the remaining 20% are gas turbines. The average ozone-forming potential for U.S. fossil-fuel power plants was calculated as 3.86 grams per gram of VOC. With ozone-forming potential of 3.42 grams per gram of NMOG for gasoline vehicles, an RAF of 1.13 was calculated for electricity.

Table 3 Emission Comparison among Best-Designed AFVs and GVs

Vehicle Model	NMOG	NMOG-RAF[a]	CO	NO_x
1990 Dedicated M85 Lumina:				
Grams-per-Mile Emissions:				
with cc catalyst[b]	0.10	0.041	0.80	0.22
without cc catalyst[c]	0.13	0.053	1.45	0.44
1990 Gasoline Lumina (w/o cc catalyst)[d]	0.18	0.18	1.65	0.48
1990 Gasoline Lumina (w/ cc catalyst)[e]	0.30	0.30	1.01	0.61
Emission Changes by the M85 Lumina (%):				
with cc catalyst	-66.7	-86.3	-20.8	-63.9
without cc catalyst	-27.8	-70.6	-12.1	-8.3
1991 M85 FFV Spirit:				
grams-per-Mile Emissions:				
with cc catalyst[f]	0.13	0.051	1.02	0.37
without cc catalyst[g]	0.17	0.070	1.24	0.35
1992 gasoline Acclaim (without cc cat)[h]	0.086	0.086	0.88	0.35
1992 gasoline Acclaim (with cc cat)[i]	0.075	0.075	0.67	0.21
Emission Changes by the FFV Spirit (%):				
with cc catalyst	73.3	-32.0	52.2	76.2
without cc catalyst	97.7	-18.6	40.9	0.0
1993 Dedicated CNG Ram Van:				
Grams-per-Mile Emissions[j]:				
CNG van	0.02	0.004	1.3	0.02
B350 Gasoline van	0.27	0.27	3.8	0.15
Emission Changes by the CNG Ram van (%):	-92.6	-98.5	-65.8	-86.7
1990 Dual-Fuel CNG Astro Van:				
Grams-per-Mile Emissions:				
CNG Astro van[k]	0.111	0.020	0.87	0.207
Gasoline Astro van[l]	0.34	0.34	4.5	0.59
Emission Changes by the CNG Astro van (%):	-67.4	-94.1	-80.7	-64.9

Table 3 (Cont.)

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[a] RAF-adjusted NMOG emissions. See Table 2 for RAFs for different fuels.

[b] Emissions of the 1990 dedicated M85 Lumina with an additional close-coupled (cc) catalyst were from Auto/Oil program.[10] When tested, the Lumina accumulated a mileage of 2,000 miles for the engine, but equivalent 6,000 miles for exhaust system components. It was designed to meet California's transitional low-emission vehicle standards of 0.125 grams per mile for NMOG, 3.4 grams per mile for CO, and 0.4 grams per mile for NO_x.

[c] Emissions of the 1990 dedicated M85 Lumina without cc catalyst were estimated from emissions of the Lumina with cc catalyst and cc catalyst's emission reductions of 21.6% for NMOG, 44.8% for CO, and 50.0% for NO_x. These emission reduction rates were calculated from emissions of a 1988 Corsica FFV fueled with M85.[11]

[d] Emissions of the 1990 gasoline Lumina without cc catalyst were from EPA's emission certification database.[12] The vehicle tested for emission certification had about 4,000 miles accumulated.

[e] Emissions of the 1990 gasoline Lumina with a cc catalyst were estimated from emissions of the 1990 gasoline Lumina without a cc catalyst and the cc catalyst's emission reductions of 69.2% for NMOG and 27.3% for NO_x, but an emission increase of 38.9% for CO. These emission change rates were calculated from emissions of a 1988 Corsica FFV fueled with gasoline.[11]

[f] Emissions of the 1991 FFV Spirit were from Auto/Oil Program.[13] The FFV was equipped with a sequential fuel injection system and with a cc catalyst.

[g] Emissions of the 1991 FFV Spirit without a cc catalyst were estimated from emissions of the FFV Spirit with a cc catalyst and the cc catalyst's emission reductions of 21.4% for NMOG and 17.7% for CO, but emission increase of 5.9% for NO_x. These emission change rates were calculated from emissions of a 1989 FFV Spirit with a cc catalyst and a 1989 FFV Caravan without a cc catalyst.[13]

[h] Emissions of the 1992 gasoline Acclaim were from the EPA's emission certification database.[14]

[i] Emissions of the 1992 gasoline Acclaim with a cc catalyst were estimated from emissions of the 1992 gasoline Acclaim without a cc catalyst and the cc catalyst's emission reductions of 12.8% for NMOG, 23.8% for CO, and 40.5% for NO_x. These emission reduction rates were calculated from emissions of a 1989 FFV Spirit with a cc catalyst and a 1989 Caravan without a cc catalyst when both were fueled with gasoline.[13]

[j] From Chrysler Corporation.[15] The CNG Ram van was equipped with a sequential multi-point fuel injection system designed for gaseous natural gas, a specially-formulated catalytic converter with large catalyst loading for NO_x control, and an engine with lower combustion temperature to reduce engine-out NO_x emissions.

[k] Emissions of the 1990 CNG Astro van were from CARB.[7]

[l] Emissions of the 1990 gasoline Astro van were from EPA's emission certification database.[12]

Table 4 Scenarios of AFV Exhaust Emission Reductions (as a Percentage of GV Emissions)

	NMOG	NMOG-RAF[a]	CO	NO_x
Low-Emission Reduction Scenario[b]				
M85 FFVs	20	-49.8	0	0
M100 FFVs	10	-58.4	0	0
M85 Dedicated Vehicles	0	-58.2	-10	0
M100 Dedicated Vehicles[c]	-10	-65.9	-10	0
E85 FFVs	20	-22.8	0	0
Dual-Fuel LPGVs	-30	-64.3	-20	0
Dual-Fuel CNGVs	-30	-87.1	-20	0
Dedicated CNGVs	-40	-89.0	-30	0
EVs	-97	-96.5	-97	-70
High-Emission Reduction Scenario[d]				
M85 FFVs	0	-58.2	-10	-10
M100 FFVs	-10	-66.0	-10	-10
M85 Dedicated Vehicles	-30	-70.7	-20	-10
M100 Dedicated Vehicles[c]	-40	-77.3	-30	-20
E85 FFVs	0	-35.7	-10	-10
Dual-Fuel LPGVs	-60	-79.6	-40	0
Dual-Fuel CNGVs	-60	-92.6	-40	0
Dedicated CNGVs	-70	-94.5	-50	-10
EVs	-100	-100	-100	-100

[a] RAF-adjusted NMOG emission reduction rate. The rate was calculated as: $(RAF_{af}/RAF_{rfg}) \times (1+EC_{NMOG}) - 1$. Where RAF_{af} is RAF for a given alternative fuel and RAF_{rfg} is RAF for reformulated gasoline (Table 2), EC_{NMOG} is emission change of mass NMOG presented in this table.

[b] This scenario was mainly based on emission reductions summarized in Figure 1. Under this scenario, emission reduction of NO_x for each AFV type, except for EVs, was assumed to be zero because all AFVs will probably be subject to the same NO_x standards as GVs will, and because there is no engineering reason why internal combustion engine AFVs emit NO_x emissions less than GVs.

[c] Emission reductions of M100 dedicated vehicles were simply assumed to be larger than those of M85 dedicated vehicles.

[d] This scenario was partially based on emission reductions of the best-designed AFVs presented in Table 3.

Table 5 Scenarios of AFV Evaporative Emission Reductions (as a Percentage of GV Evaporative Emissions)

	Low-Emission Reduction		High-Emission Reduction	
Vehicle type	NMOG	NMOG-RAF[a]	NMOG	NMOG-RAF[a]
M85 FFVs	0	-58.2	-20	-66.6
M100 FFVs	-20	-69.8	-40	-77.3
M85 Dedicated Vehicles	-50	-79.1	-80	-91.6
M100 Dedicated Vehicles	-50	-81.1	-80	-92.4
E85 FFVs	0	-35.7	-20	-48.6
Dual-Fuel LPGVs	-100	-100.0	-100	-100.0
Dual-Fuel CNGVs	-100	-100.0	-100	-100.0
Dedicated CNGVs	-100	-100.0	-100	-100.0
EVs	-100	-100.0	-100	-100.0

[a] Emission reductions of RAF-adjusted NMOG are calculated as: $(RAF_{af}/RAF_{rfg}) \times (1+EC_{NMOG}) - 1$. Where RAF_{af} is RAF for a given alternative fuel type, RAF_{rfg} is RAF for reformulated gasoline (Table 2), and EC_{NMOG} is change of mass NMOG evaporative emissions. There was no information on RAFs for NMOG evaporative emissions from different AFV types. RAFs for exhaust NMOG emissions were used here.

Table 6 Weight Percentage of Air-Toxic Pollutants in NMOG Emissions[a]

	1,3-Butadiene	Benzene(exh.)	Formaldehyde	Acetaldehyde	Benzene(evap.)
Gasoline[b]	0.37	6.92	1.46	0.93	0.63
M85	0.07	0.98	5.04	0.23	2.00[d]
E85	0.07	0.50	1.86	7.82	2.00[e]
LPG	0.05	0.41	3.0	0.88	N/A[f]
CNG	0.02	0.19	4.46	0.61	N/A[f]
Electricity[c]	0.00	0.48	3.84	0.00	N/A[f]

[a] From CARB.[7]

[b] The gasoline blend RF-A developed by the Auto/Oil program was used in GVs.

[c] Weight percentages of the four air-toxic pollutants in VOC emissions for electricity generation were calculated as follows. From EPA's air toxic speciated database,[8] it was found that formaldehyde accounted for 30% of VOC emissions for natural gas turbines, 8% for natural gas boilers, and 42% for residual oil boilers; that benzene accounted for 4% of VOC for natural gas boilers. Emissions of other air-toxic pollutants from oil and natural gas power plants were zero. There was no presence of the four pollutants in VOC emission from coal-fired power plants. An electricity generation mix of 55% for coal-fired plants, 14% for natural gas-fired plants, and 5% was used for oil-fired plants to calculate utility average air toxic distribution.[9] In addition, 20% of natural gas-fired plants was assumed to equip with gas turbines, and the remaining 80% with utility boilers.

[d] Benzene content of 2% was assumed for M85 FFVs and M85 dedicated vehicles, and 1.5% was assumed for M100 FFVs and M100 dedicated vehicles.[17]

[e] It was assumed that benzene weight percentage in HC emissions from E85 FFVs was the same as that from M85 FFVs.

[f] Not applicable because there are no evaporative emissions from these fuels.

Table 7 Emission Changes of Four Air-Toxic Pollutants by Alternative-Fuel Vehicles (as a Percentage of GV Emissions)

	1,3-Butadiene	Benzene(exh.)	Formaldehyde	Acetaldehyde	Benzene(evap.)
Low-Emission Reduction Scenario					
M85 FFVs	-77.3	-83.0	314.2	-70.3	215.5
M100 FFVs[a]	-79.2	-84.4	279.7	-72.8	89.3
M85 Dedi. Vehicles	-81.1	-85.8	245.2	-75.3	57.7
M100 Dedi. Vehicles[a]	-83.0	-87.3	210.7	-77.7	18.3
E85 FFVs	-77.3	-91.3	52.9	909.0	215.5
LPGVs	-90.5	-95.9	43.8	-33.8	-100.0
Dual-Fuel CNGVs	-96.2	-98.1	113.8	-54.1	-100.0
Dedicated CNGVs	-96.8	-98.4	83.3	-60.6	-100.0
EVs	-100.0	-99.8	-92.1	-100.0	-100.0
High-Emission Reduction Scenario					
M85 FFVs	-81.1	-85.8	245.2	-75.3	152.4
M100 FFVs[a]	-83.0	-87.3	210.7	-77.7	42.0
M85 Dedi. Vehicles	-86.8	-90.1	141.6	-82.7	-36.9
M100 Dedi. Vehicles[a]	-88.6	-91.5	107.1	-85.2	-52.7
E85 FFVs	-81.1	-92.8	27.4	740.9	152.4
LPGVs	-94.6	-97.6	-17.8	-62.2	-100.0
Dual-Fuel CNGVs	-97.8	-98.9	22.2	-73.8	-100.0
Dedicated CNGVs	-98.4	-99.2	-8.4	-80.3	-100.0
EVs	-100.0	-100.0	-100.0	-100.0	-100.0

[a] There were no speciated NMOG data for M100 (either FFVs or dedicated-fuel vehicles). Speciated NMOG data for M85 vehicles were used for M100 vehicles.

Table 8 Incremental Prices of AFVs Over The Price of GVs[a]

Vehicle type	Low-Cost Scenario	High-Cost Scenario
Methanol FFVs	400	800
Dedicated MVs	0	300
Ethanol FFVs	400	800
Dual-Fuel LPGVs	800	1,700
Dual-Fuel CNGVs	1,500	2,500
Dedicated CNGVs	1,000	2,000

[a] Subcompact cars, 1990 $.

Table 9 Annual VMT and Maintenance Costs of a Compact Gasoline Car[a]

Age (yrs)	Annual VMT	Maintenance Cost[b] (1990 $)
1	12,900	131.53
2	12,600	288.69
3	12,300	367.71
4	11,900	414.70
5	11,500	447.39
6	11,000	468.08
7	10,600	477.01
8	10,100	488.33
9	9,600	487.51
10	9,100	489.19
11	8,700	86.32
12 and up	8,200	478.25

[a] From FHWA.[19]

[b] Including scheduled costs, unscheduled costs, and the cost of engine oil changes.

Table 10 Scenarios for Fuel Prices

	CEC's Estimate[a]	Low-Cost Scenario	High-Cost Scenario
Ref. Gasoline ($/gal.)	1.43	1.22[b]	1.64[c]
Methanol ($/gal.)	0.82-1.02	0.82[d]	1.02[e]
Ethanol ($/gal.)	1.19-1.87	1.19[d]	1.87[e]
CNG ($/mmBtu)	10.01	8.00[f]	11.00[g]
LPG ($/gal.)	0.90	0.75[h]	1.21[i]
Electricity (cents/Kwh)	5.5	6.5[j]	11.0[k]

[a] CEC.[24] A federal road excise tax of $0.14 per gallon of gasoline and a state road excise tax of $0.18 per gallon were included for all fuels but electricity. CEC's estimates are presented here as a comparison to the price scenarios.

[b] Assumed to be 85% of the gasoline price estimated by CEC.

[c] Assumed to be 115% of the gasoline price estimated by CEC.

[d] The lower price estimated by CEC is used.

[e] The higher price estimated by CEC is used.

[f] Based on the estimates by the EPA and American Gas Association. The EPA[25] estimated CNG price ranging from $6.70 to $10.78 per mmBtu, with a median value of $8.7 per mmBtu. American Gas Association[26] estimated CNG price of $7.28 per mmBtu.

[g] Based on CNG prices estimated by CEC and by the EPA. The EPA[25] estimated a higher CNG price of $10.78 per mmBtu.

[h] Based on Osgood.[23]

[i] LPG price was assumed to be the same as gasoline price on an energy equivalent basis.

[j] A price for off-peak electricity lower than CEC's estimated price was assumed. A road tax of 2 cents per Kwh equivalent to per-mile gasoline road tax was included.

[k] A higher electricity price was assumed. A road tax of 2 cents per Kwh equivalent to per-mile gasoline road tax was included.

Table 11 Performance and Cost Assumptions of Low-Cost and High-Cost EV Battery Scenarios[a]

	High Cost	Low Cost
Unit Retail Price of Battery ($/Kwh)	150	100
Life Cycles	600	1,000
Energy Density (wh/kg)[b]	80	200
EV Driving Range (miles)[c]	125	200
EV Electricity Use (Kwh/mile)	0.4	0.35
Total Battery Capacity (Kwh)[d]	64.1	87.5
Cost per Battery ($)[e]	9,375	8,750
Total Miles Accumulated per Battery[f]	63,750	170,000

[a] Most performance and cost goals are established by USABC,[28] except as noted.

[b] Measured with 3-hour constant battery discharge.

[c] Assumed in this study.

[d] Total battery capacity was calculated as: EV driving range (miles)/depth of discharge x EV electricity use (Kwh/mile). Depth of discharge for batteries represents the fact that EV batteries cannot be discharged to zero electricity because doing so may shorten battery life dramatically. A depth of discharge of 80% was assumed.

[e] Cost per battery was calculated as total battery capacity multiplied by per-unit-of-energy price of battery.

[f] Total miles accumulated per battery was calculated as battery life cycles multiplied by average travel distance per cycle. The average travel distance per cycle was assumed here to be 85% of the designed EV driving range.

Table 12 Percent Value of Life-Cycle Cost Increases by AFVs over GVs (1990 $)

Vehicle type	Low-Cost Case[a]	High-Cost Case[b]
M85 FFVs	1,236	1,541
M100 FFVs	1,564	1,872
M85 Dedicated Vehicles	373	478
M100 Dedicated Vehicles	689	780
E85 FFVs	1,238	2,867
Dual-Fuel LPGVs	2,001	4,241
Dual-Fuel CNGVs[c]	-74	668
Dedicated CNGVs[c]	-738	-51
EVs[d]	629	11,558

[a] The low-cost case is the calculating results with scenarios of low incremental vehicle prices and low fuel prices.

[b] The high cost case is the calculating results with scenarios of high incremental vehicle prices and high fuel prices.

[c] The life-cycle cost differences for CNGVs (both dual-fuel and dedicated) were calculated by assuming that CNGVs lasted 13 years. To calculate costs of GVs for 13 years, a first GV was assumed to last for 12 years, and another GV was introduced in year 13. The price of the second GV was annualized over 12 years. The annual cost of the second car in year 13 was calculated by adding annualized vehicle price, annual fuel cost and maintenance cost. Cost of GVs over the 13 years was the total of the cost of the first GV and the first year cost of the second GV.

[d] The life-cycle cost differences for EVs were calculated by assuming that EVs lasted 15 years. To calculate costs of GVs over the 15 years, a first GV was assumed to last for 12 years, and another GV was introduced in year 13. The price of the second GV was annualized over 12 years. The annual cost of the second car between year 13 and year 15 was calculated by adding annualized vehicle price, annual fuel cost and maintenance cost. Cost of GVs over 15 years was the total of the cost of the first GV and the first three-year cost of the second GV.

Table 13 Emission Rates and Total Emissions of a 1995 Model-Year Gasoline Car

	Emission Rates (grams/mile)[a]				Annual Emissions (pounds/year)[b]			
Calendar Year	NMHC (exh.)[c]	NMHC (evap.)[d]	CO	NO_x	NMHC (Exh.)[c]	NMHC (evap.)[d]	CO	NO_x
1995	0.229	0.274	2.623	0.291	8.13	6.50	74.55	8.27
1996	0.289	0.276	4.026	0.376	10.02	8.02	111.73	10.44
1997	0.378	0.281	6.140	0.507	12.79	10.23	166.35	13.74
1998	0.459	0.288	8.087	0.631	15.05	12.04	211.97	16.54
1999	0.535	0.294	9.912	0.748	16.95	13.56	251.07	18.95
2000	0.820	0.330	14.052	1.005	24.83	19.87	340.47	24.35
2001	1.079	0.364	17.825	1.249	31.05	25.20	416.18	29.16
2002	1.317	0.398	21.299	1.480	36.62	29.29	473.83	32.93
2003	1.542	0.432	24.574	1.698	40.75	32.60	519.63	35.90
2004	1.748	0.466	27.595	1.905	43.80	35.04	553.12	38.18
2005	1.926	0.500	30.222	2.103	46.13	36.90	579.14	40.30
2006	2.102	0.535	32.798	2.290	47.45	37.96	592.39	41.36
2007[e]	0.182	0.122	2.620	0.221	4.12	3.29	47.32	3.99
2008[e]	0.242	0.122	4.024	0.305	5.45	4.36	72.68	5.51
2009[e]	0.410	0.126	6.138	0.437	7.44	5.95	110.86	7.89

[a] Calculated with Mobile5A.

[b] Calculated with the grams-per-mile emission rates presented in this table and annual VMT presented in Table 9.

[c] Exhaust NMHC emissions.

[d] Evaporative NMHC emissions. Evaporative emissions here include diurnal, hot soak, running losses, resting losses, and refueling emissions.

[e] A new GV was assumed to be introduced in 2007. Thus, emissions in years 2007-2009 are for this new GV.

Table 14 PV of Life-Cycle Emission Reductions by AFVs (Pounds)[a]

	NMOG-RAF	CO	NO_x	1,3-but	Benzene	Formal	Acetal.
Low-Emission Reduction Scenario							
M85 FFVs	202.2	0.0	0.0	0.60	9.76	-9.62	1.37
M100 FFVs	239.7	0.0	0.0	0.61	11.30	-8.57	1.42
M85 Dedi. Vehicles	254.8	269.5	0.0	0.63	11.84	-7.51	1.48
M100 Dedi. Vehicles	274.4	269.5	0.0	0.64	12.48	-6.45	1.52
E85 FFVs	107.7	0.0	0.0	0.60	10.96	-1.62	-17.73
LPGVs	302.7	539.0	0.0	0.70	14.99	-1.34	0.66
Dual-Fuel CNGVs	350.6	539.0	0.0	0.75	15.31	-3.49	-1.06
Dedicated CNGVs	354.5	808.5	0.0	0.75	15.36	-2.55	1.18
EVs	383.4	2711.7	143.5	0.80	16.10	2.92	2.02
High-Emission Reduction Scenario							
M85 FFVs	600.1	1078.0	19.8	2.52	48.20	-30.04	5.88
M100 FFVs	683.6	1078.0	19.8	2.58	50.25	-25.81	6.06
M85 Dedi. Vehicles	747.0	2156.0	19.8	2.69	52.71	-17.35	6.45
M100 Dedi. Vehicles	803.7	3233.9	39.5	2.75	53.69	-13.12	6.65
E85 FFVs	381.1	1078.0	19.8	2.52	52.27	-3.36	-57.82
LPGVs	835.8	4311.9	0.0	2.94	57.74	2.18	4.85
Dual-Fuel CNGVs	944.9	4311.9	0.0	3.04	58.49	-2.72	5.76
Dedicated CNGVs	960.8	5389.9	19.8	3.06	58.67	1.03	6.27
EVs	1042.7	11182.1	205.1	3.22	61.23	12.69	8.08

[a] PV of AFV life-cycle emission reductions was calculated with baseline GV emissions and AFV emission reduction rates. A positive number means emission decrease, while a negative number means emission decrease.

Table 15 Calculation and Results of Weighing Factors of Seven Pollutants

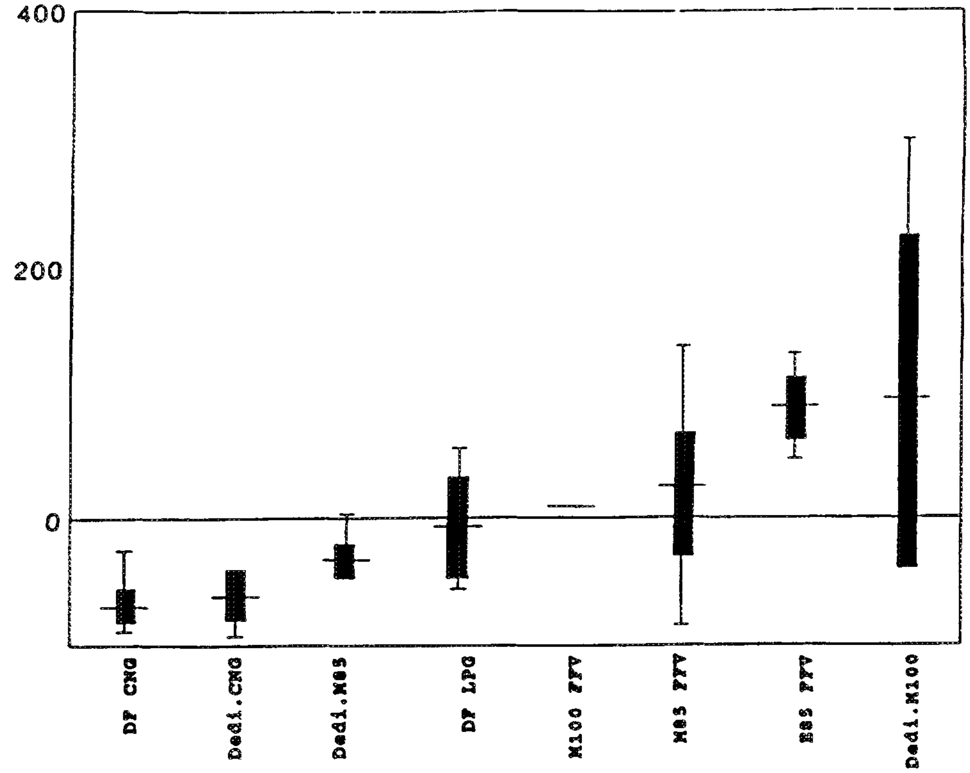
Pollutant			Weighing Factor
Three Criteria Pollutants:			
	Damage Value (\$/ton)[a]		
NMOG	18,600		1
CO	9,300		0.49
NO_x	26,400		1.40
Five Air Toxic Pollutants:			
	Unit Risk[b]	Residence Time (hour)[c]	
Benzene	8.3×10^{-6}	198	10[d]
1,3-buta.	2.8×10^{-4}	5.5	9.37
Formalde.	1.3×10^{-5}	16.5	1.31
Acetalde.	2.2×10^{-6}	22.5	0.31

[a] These damage values were estimated by California Energy Commission for California's South Coast Air Basin.[32]

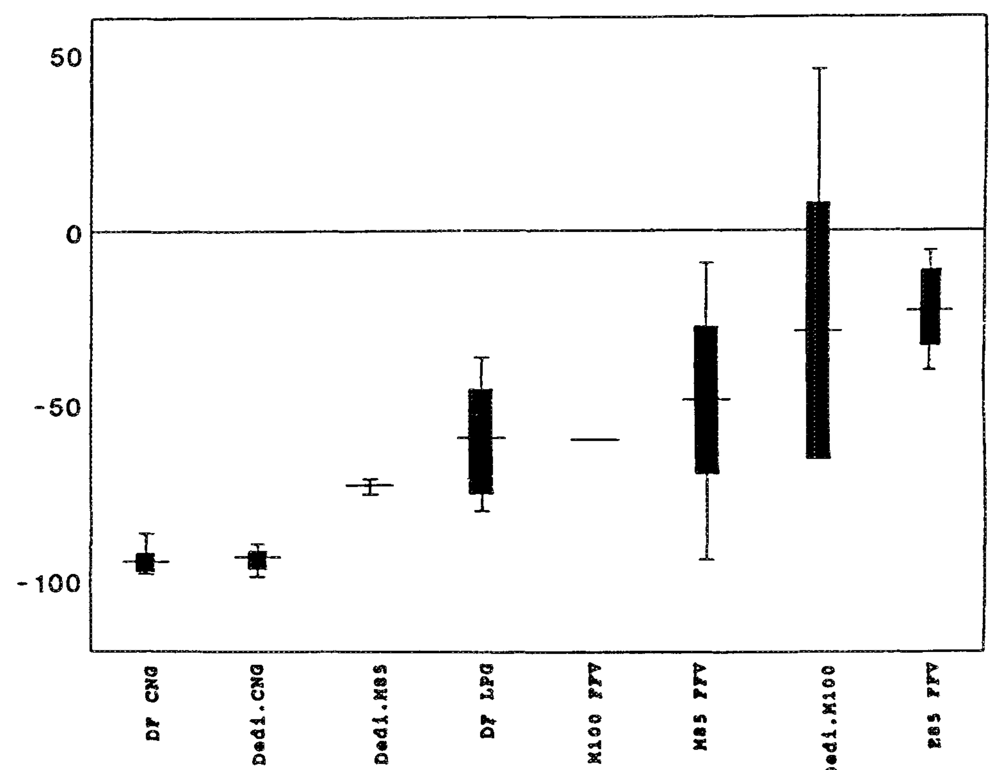
[b] Unit cancer risk is the excess lifetime cancer risk due to continuous constant lifetime exposure to one ug/m^3 of carcinogen concentration. These risk factors were from U.S. EPA.[33]

[c] This is the average residence time each pollutant lasts in the atmosphere.[33] Risk factor for any other toxic pollutant relative to the toxicity of benzene was calculated by multiplying unit risk factor and residence time. The multiplying result was divided by the multiplying result for benzene.

[d] Assumed in this study.

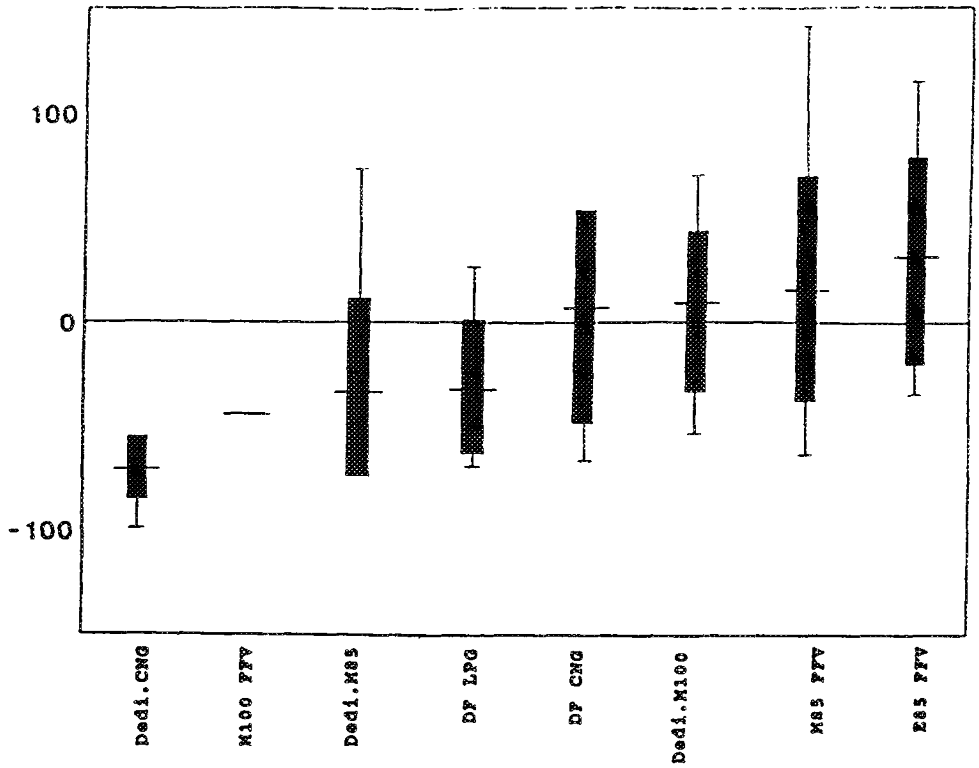


(a) Mass NMOG Emissions

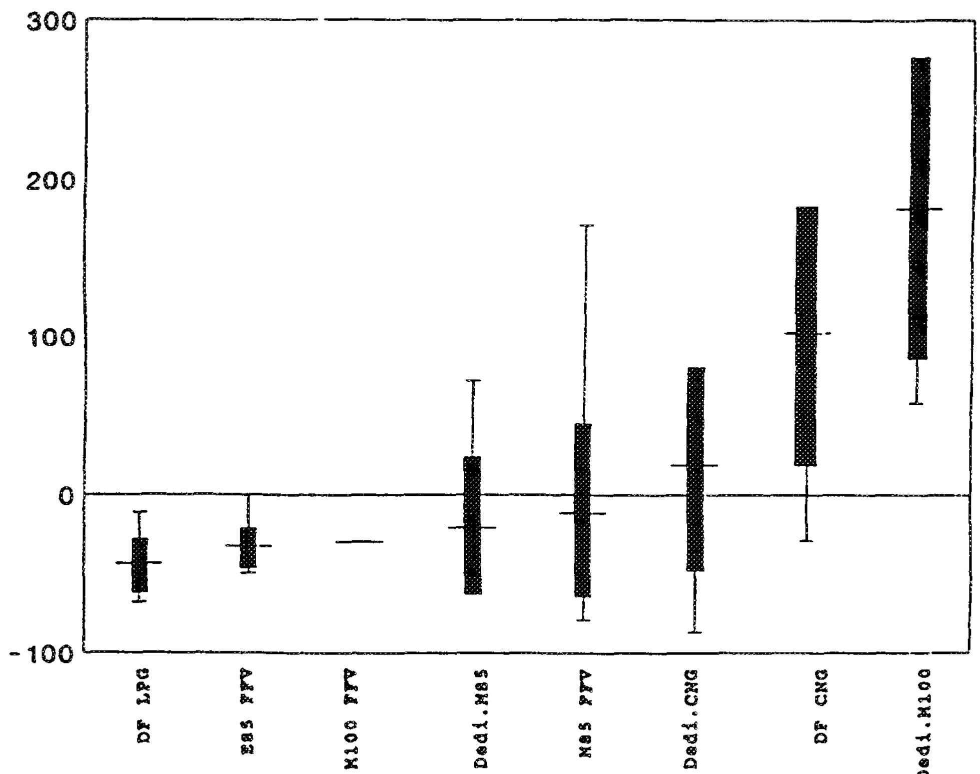


(b) RAF-Adjusted NMOG Emissions

Figure 1 Means, Standard Deviations, Minimum Values, and Maximum Values of Emission Changes by Alternative-Fuel Vehicles



(c) CO Emissions



(d) NO_x Emissions

Figure 1 (Cont.)

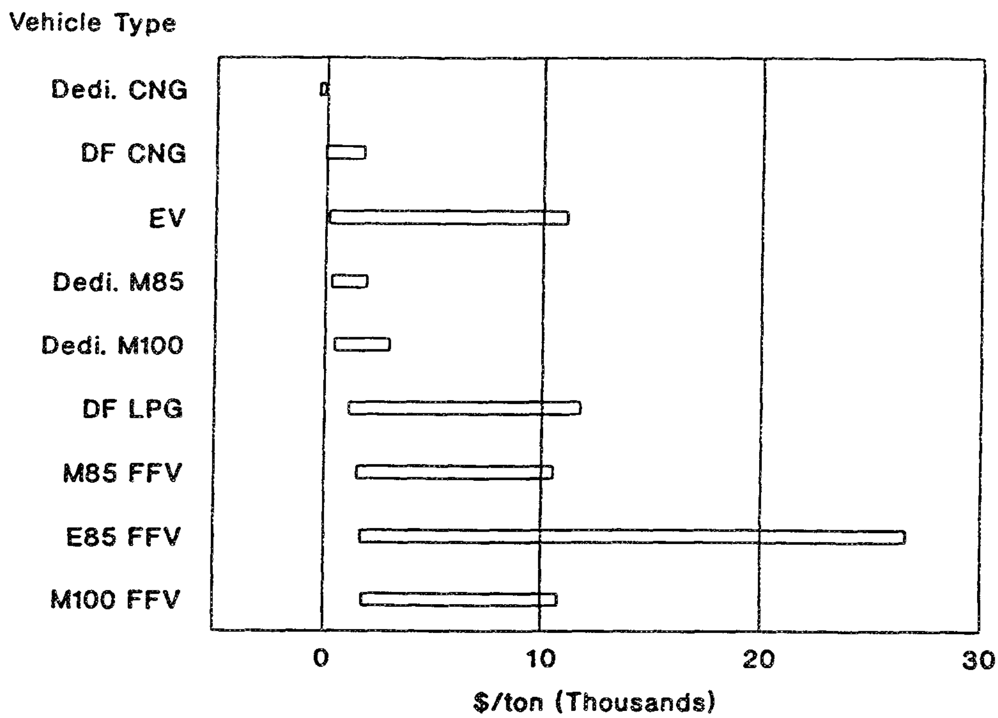


Figure 2 Emission Control Cost-Effectiveness of AFVs, Including Air-Toxic Pollutants

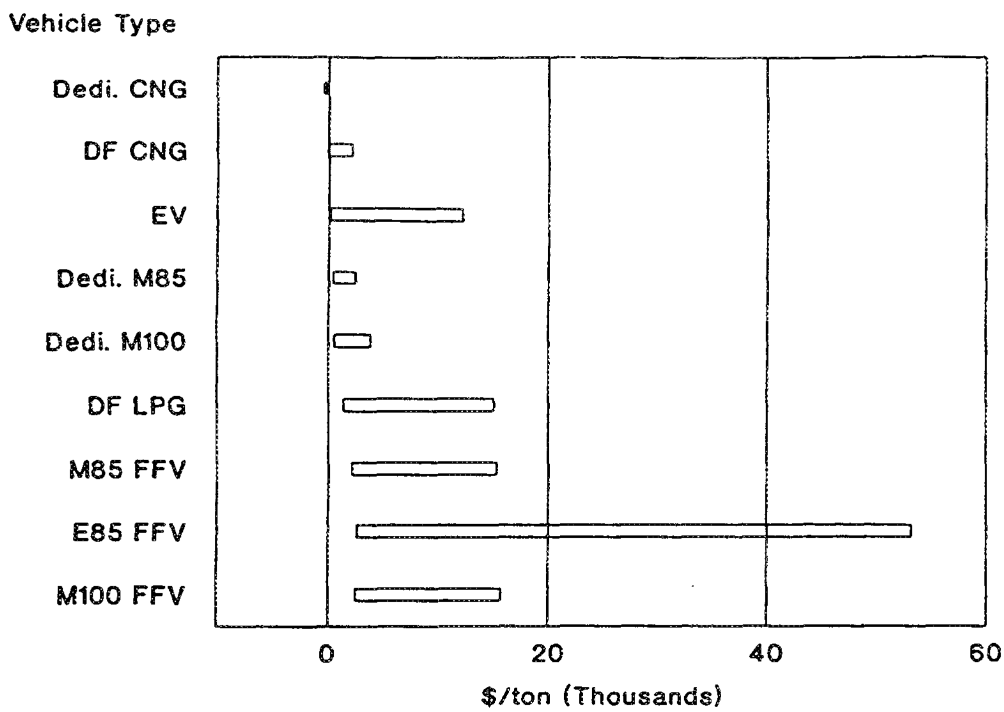


Figure 3 Emission Control Cost-Effectiveness of AFVs, Excluding Air-Toxic Pollutants