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A ZEV Credit Scheme for Zero-Emission Heavy-Duty Trucks

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Executive Summary

Zero and near-zero emission vehicles based on electric-drive technology have the potential to play a long-term role in alleviating the air pollution, greenhouse gas, and energy use concerns associated with conventional vehicles. Most attention has focused on electric-drive technologies for light-duty vehicles (LDVs), but some electric-drive technologies are also suitable for heavy-duty vehicle (HDV) applications.

HDVs are in fact particularly attractive targets for zero-emission technology because they produce a disproportionate share of motor vehicle pollution in California and the U.S. HDVs are largely based on diesel engine technology, and these diesel engines produce high emission levels of oxides of nitrogen (NOx) and fine particulates (PM_{10}). PM_{10} emissions in particular are increasingly seen as having the most serious health effects of all vehicle pollutants. Furthermore, the vast majority of HDV travel is by heavy-duty trucks (HDTs), but these vehicles are at present less-stringently regulated than urban transit buses (particularly given the recent CARB regulation to reduce urban transit bus emissions beginning in 2002).

In order to investigate the potential of stimulating the development of zero-emission HDTs, and their introduction into California-based HDT fleets, this report anlayzes the potential for broadening the ZEV mandate to allow manufacturers of zero-emission HDTs to be awarded ZEV credits. The report analyzes the average relative emission levels of carbon monoxide (CO), hydrocarbons (HCs), NO_x, and PM_{10} from LDVs and HDTs in California, as estimated in the latest version of the CARB mobile source emission inventory model, EMFAC2000. Using these estimates of the relative emission reduction potential of zero-emission LDVs and medium and heavy HDTs, along with estimates of the average annual mileage for these vehicle classes, potential ZEV credit award levels for zero-emission HDTs are estimated.

The findings are that from 42 to 226 ZEV credits could in principle be justified to be awarded to manufacturers of zero-emission HDTs, depending on the model year of their introduction (from 2001 to 2010) and the HDT weight class, if the four pollutants are weighted according to their approximate relative damage values. These damage values reflect the impact on each pollutant to human health in major California urban areas. Using a simpler scheme that does not consider the relative damages from the pollutants, and that weights each pollutant equally, potential ZEV credit award levels range from 24 to 100 credits for zero-emission HDTs.

Introduction

Zero and near-zero emission vehicles based on electric-drive technology have the potential to play a long-term role in alleviating the air pollution, greenhouse gas, and energy use concerns associated with conventional vehicles. While most attention has focused on electric-drive technologies for light-duty vehicles, some electric-drive technologies are also suitable for heavy-duty vehicle (HDV) applications. These include electric propulsion systems that are battery powered but hybridized with a diesel or natural gas powered generator set, and those that are fuel cell powered.

Of these options, only HDVs with fuel cell/electric motor propulsion systems have the potential to completely eliminate tailpipe emissions.[1] An HDV with a hybrid propulsions system could produce significantly less pollution than a conventional diesel truck, but some emissions would necessarily be produced from the hybrid HDV's fuel-fired generator system. In contrast, fuel cell powered HDVs could be designed to produce no direct emissions by using hydrogen fuel that is stored onboard. This hydrogen fuel could be provided at a refueling station, or produced onboard the vehicle from water and electricity with an electrolyzer device.

It is also noteworthy that in addition to reducing emissions of criteria pollutants, these heavy-duty zero-emission vehicle (ZEV) technologies can also lead to reductions in greenhouse gas emissions. These reductions could be expected due to potential increases in vehicle efficiency, and the potential use of fuels with lower associated greenhouse gas emissions than diesel. Furthermore, they offer the potential of using renewable sources of energy rather than fossil fuels. Battery powered vehicles can be recharged with solar, wind, and hydro-electric power, hybrid vehicles can combust biodiesel or ethanol to produce electricity, and fuel cell vehicles can use hydrogen derived through solar, wind, and hydro-powered electrolysis, or certain biological processes.[2] Several battery, hybrid, and fuel cell powered buses have been built and are undergoing testing, and hybrid and fuel cell powered trucks are also under development.

Thus, heavy-duty vehicles that incorporate electric-drive technology have the possibility of advancing a range of social goals. However, the main benefits that they offer are no doubt related to their potential to reduce the criteria pollutant emissions from conventional HDVs. HDVs powered with diesel fuel are well known to be high emitters of nitrogen oxides (NO_x) and fine particulate matter (PM_{10}). These two pollutants are of concern because of the ozone-forming potential of NO_x and the direct

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[1] Purely battery powered HDVs are possible, but they are relatively impractical for most applications because of the tremendous mass of batteries required to power such large vehicles.

[2] Recent advances have been announced in the generation of hydrogen with algae, and also with alkaline hydride-based hydrogen storage and release systems.

and adverse human health impacts of PM_{10}. Due to their relatively high levels of emissions of these two pollutants, HDVs are thus good targets for zero and near-zero emission technologies.

This report develops a few possible ZEV credit schemes for HDVs, with a particular focus on ZEV credits for the heavy-duty truck (HDT) class of vehicles.[3] This class of vehicles is a particularly attractive niche for electric-drive technology because conventional HDTs are predominantly diesel-fueled, with high associated emissions, and because HDTs are used intensively, with average annual mileages of 30,000 to 40,000 miles per year (Davis, 1997).[4] Therefore, this report focuses on a ZEV credit scheme for zero-emission HDTs, although in principle other HDV classes could be included as well.

This report assesses estimates of criteria pollutant emissions from HDTs, relative to emissions from light-duty gasoline vehicles, and then presents potential schemes for awarding ZEV credits to manufacturers of zero-emission medium HDTs and heavy HDTs. The suggested ZEV credit values are based on the relative emission reductions of incorporating zero-emission drivetrain technologies into HDTs and light-duty vehicles (LDVs). The proposed HDT ZEV credit schemes include one that estimates the pollutant reduction potential of zero-emission HDTs, relative to light-duty ZEVs, and then weights the relative impacts of carbon monoxide (CO), hydrocarbons (HCs), NO_x, and PM_{10} according to their approximate human health damage values. A second scheme is shown that does not weight the pollutants by damage values and instead calculates the simple average of the emission reduction potential across pollutants.

Finally, based on the relative merits of these proposed HDT ZEV credit schemes, policy recommendations are made with regard to the potential adoption of such a scheme in future revisions of the California Air Resources Board ZEV mandate. The Board may wish to consider such a scheme because a revision of the ZEV mandate that included an avenue for awarding ZEV credits to manufacturers of zero-emission HDTs would build additional flexibility into the LEV II/ZEV regulations. This flexibility would arise from allowing the possibility for manufacturers of LDVs to purchase ZEV credits from zero-emission HDT manufacturers, and this could be valuable in early years of the ZEV mandate when LDV manufacturers might otherwise have difficulty meeting their mandated production of ZEVs. A scheme for awarding ZEV credits to zero-emission HDT manufacturers would have the particular appeal of potentially helping to reduce

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[3] Heavy-duty trucks are defined for purposes of this report as trucks with a gross vehicle weight rating of 8,500 pounds or more, matching the definition of heavy-duty trucks used in the CARB MVEI series of vehicles emission models. Medium HDTs are defined as having a weight class between 14,001 and 33,000 pounds, and heavy HDTs are defined as having a gross vehicle weight rating of 33,001 to 66,000 pounds, again corresponding with the definitions used in the MVEI emission models.

[4] Although surprisingly over 70% of HDTs have daily operating ranges of 100 miles or less (Davis, 1997), suggesting that even limited range ZEV technologies can be suitable for most HDTs.

emissions from the HDT sector, which as discussed below produces a disproportionate share of emissions of NO_x and PM_{10}.

The California ZEV Mandate

The original 1990 California ZEV program (known as the "ZEV mandate") was adopted by the California Air Resources Board (CARB) in September of 1990 as part of the state's Low-Emission Vehicle (LEV) regulations. The original ZEV mandate required 10% of the vehicles offered for sale by major manufacturers in the state of California to be ZEVs by 2003, with 2% and 5% production requirements for 1998 and 2001. Under the definitions in the regulation, seven automakers currently qualify as "major manufacturers" that produce over 35,000 vehicles per year for the California market. These include DaimlerChrysler, Honda, Ford, General Motors, Mazda, Nissan, and Toyota. In 2003, intermediate-sized manufacturers (with California production between 4,000 and 35,000 vehicles per year) also were to be bound by the 10% ZEV production requirement. New York and Massachusetts subsequently adopted the same requirements as California, approximately doubling the number of ZEVs required to be produced (CARB, 1998a).

In 1996, under the biennial review process included in the LEV program, the ZEV mandate was changed to lift the requirements for production prior to 2003. The 2% and 5% production requirements were replaced by "memoranda of understanding" with automakers to produce a smaller number of vehicles, on the order of a few hundred for each manufacturer. Then, in 1998, under the subsequent biennial review, the mandate was changed again to allow some of the 10% ZEV requirement for 2003 to be composed of "partial ZEV credits" from other "near-ZEVs" that meet a complex set of emission-related and other technological criteria. However, even under the new, more flexible regulations, at least 40% of the ZEV credits required of major manufacturers, or 4% of overall production for California, must come from "true ZEVs" that emit no criteria pollutants directly from their tailpipes (CARB, 1998a and 1998b).

Under the revised regulation, manufacturers can receive partial ZEV credits for non-ZEVs if the vehicles certify to super-low emission vehicle (SULEV) exhaust emission standards, certify to "zero" evaporative emission standards,[5] certify to meet the applicable on-board diagnostic requirements at 150,000 miles, and have vehicle performance and defects warranty periods of at least 15 years or 150,000 miles. Manufacturers of vehicles meeting these requirements receive baseline partial ZEV credit of 0.2 credits per vehicle. Vehicles can be awarded additional partial ZEV credits if they have a zero-emission driving range of over 20 miles. Under the zero-emission driving range clause of the regulation, vehicles can receive up to 0.6 ZEV credits for

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[5] CARB is presently determining the specifics of the evaporative emission requirements, and what exactly "zero evaporative emissions" means.

zero-emission driving range, based on a formula that awards credits across a continuum of zero-emission range from 20 to 100 miles. Vehicles that do not qualify for the zero-emission range-based avenue of partial credits can alternately receive 0.1 credits if they include some form of advanced ZEV componentry. Finally, vehicles that meet the baseline partial ZEV requirements can receive up to 0.2 ZEV credits if they meet a fuel-cycle NMOG emission standard of 0.01 grams per mile (CARB, 1998a).

The California LEV program will be reviewed again in 2000, and additional revisions to the ZEV regulations are possible under this review process. CARB has scheduled a board meeting for September of 2000 to determine if additional changes to the program are warranted.

Emissions from Diesel Trucks

Emissions from diesel engines have been under intense scrutiny in recent years due to the possibility of carcinogenic effects of diesel particulates, and because of their disproportionate contribution to worsened air quality. In 1995, for example, diesel engine vehicles accounted for 26.5% of U.S. highway vehicle NO_x emissions, and emissions from heavy-duty diesel vehicles composed nearly 98% of the total NO_x emissions from these diesel engine vehicles. In general, diesel engines accounted for about 17% of NO_x emissions from all sources in the country in 1995. With regard to PM emissions, diesel engine vehicles emitted about 66% of all particulates from highway vehicles in 1995, and heavy-duty diesel vehicles were responsible for 95% of the diesel vehicle total (U.S. EPA, 1996).

The high levels of PM emissions from diesel engines contribute significantly to ambient levels of particulates in many urban areas. For example, a recent report by the Natural Resources Defense Council (NRDC) reports on 1998 monitoring work that was conducted by NRDC in conjunction with the Coalition for Clean Air. This monitoring study revealed that particulate concentrations in urban areas with heavy truck and bus traffic were as high as 50 $\mu g/m^3$ at times during the monitoring period (NRDC, 1998). Other PM analysis efforts in Stockton, Fresno, and Bakersfield frequently measured motor vehicle particulate levels of 10 $\mu g/m^3$, compared with CARB estimates of 2.2 $\mu g/m^3$ for a California statewide average and 3.6 $\mu g/m^3$ in the South Coast Air Basin (NRDC, 1998). Thus, there is some evidence that official estimates of ambient particulate levels are understated, and that motor vehicle exhaust raises ambient PM levels to levels much higher than the estimated statewide and South Coast averages in some areas.

It is also important to note that within the U.S., trucks are increasing in number and are moving an increasing proportion of freight. In 1995, 307,000 heavy-duty trucks (Class 7-8 -- over 26,000 pounds gross vehicle weight) were sold, up from 206,000 in 1990 and 175,000 in 1980 (Davis, 1997). Total U.S. registrations of heavy single-unit and combination trucks were 5.7 million in 1987, 6.0 million in 1992, and 7.1 million in 1997, and the vehicle miles traveled by these truck fleets were 123.5 billion miles, 153.4 billion miles, and 191.4 billion miles, respectively (Davis, 1999). In general, trucks seem to be increasing in number, traveling more miles, carrying heavier loads, and emitting more pollution (in absolute terms) with each passing year.

Diesel Emissions and Human Health

Diesel emissions are particularly damaging to human health because they are high in levels of particulate matter, and because the particulate matter tends to be very fine particulate matter. Such fine particulate matter, under one micron in size, goes deep into the recesses of the lungs and is not easily cleared. Furthermore, the particulates from diesel exhaust are coated with a mixture of chemicals, and these chemicals are delivered into the human body when the particles are inhaled (HEI, 1999).

Many studies have been conducted on the health effects of diesel exhaust, including 40 studies conducted by the Health Effects Institute (HEI) from 1983 to 1999. Based on these studies, HEI has concluded that there is an association between lung cancer and diesel exhaust exposure, with workers that have been exposed to diesel exhaust showing a 20% to 40% greater incidence of lung cancer than the general population (HEI, 1999). Several government agencies, including the National Institute for Occupational Safety and Health (NIOSH), the World Health Organization (WHO), and the California EPA, have concluded that laboratory studies on rats are sufficient to demonstrate the carcinogenicity of diesel exhaust. The U.S. EPA has recently released a draft report (in November, 1999) that reviews the analysis that the agency has conducted on the health effects of diesel exhaust, and that reports that the agency is currently considering whether to place diesel exhaust in the “likely” or “highly likely” category for carcinogenicity (HEI, 1999).

In California, diesel exhaust was identified as a chemical “known to cause cancer” under Proposition 65 in 1990 (CARB, 1998c). More recently, CARB has listed particulate emissions from diesel engines as a toxic air contaminant (TAC). Initially, CARB staff proposed listing “diesel exhaust” as a TAC, but the agency subsequently decided that this was too general and also inappropriate because diesel exhaust includes harmless substances such as water vapor and nitrogen. Thus, the more specific category of “particulate emissions from diesel engines” was determined to be more appropriate, and on August 27, 1998 CARB approved the staff proposal to list this category of pollutants as a TAC. The agency is now investigating the need, feasibility, and cost of measures to reduce public exposure to both the particulate matter and organic gases emitted by diesel engines (CARB, 1998c).

Also in California, the South Coast Air Quality Management District (SCAQMD) has recently completed a landmark air toxics study, known as the Multiple Air Toxics

Exposure Study (MATES II). This study consisted of a comprehensive monitoring program for the South Coast area, a revised emissions inventory of TACs, and a modeling effort to characterize the risks from TACs to human populations in the South Coast area. A draft report of the study results concludes that the average carcinogenic risk in the South Coast Air Basin is about 1,400 per million people, with mobile sources being by far the largest contributor to this risk. Furthermore, about 70% of all of the identified carcinogenic risk was attributable to diesel particulate emissions, with 20% from other mobile sources, and 10% from stationary sources. In general, the variation in cancer risk across the regions studied were driven by differences in the influence of mobile sources, with the greatest risk in areas (south-central and east-central portions of Los Angeles County) with a particularly heavy dominance of mobile source contributions (SCAQMD, 1999).

Emission Standards for Heavy Duty Vehicles

Emission standards for heavy-duty vehicles have remained relatively constant in recent years, although standards for NO_x and PM have been tightened somewhat. Also, separate and more stringent federal and California standards were promulgated for PM emissions from urban buses, beginning in 1991. Both the federal and California standards for CO have been constant at 15.5 g/bhp-hr since 1990, and standards for HCs have been constant at 1.3 g/bhp-hr. NO_x standards, on the other hand, have been ratcheted down somewhat, with the federal and California 1990 standard of 6.0 g/bhp-hr replaced with a 5.0 g/bhp-hr standard in 1991-1993 and a 4.0 g/bhp-hr standard in 1998 and thereafter (1996 and thereafter in California). PM standards also were reduced somewhat during the 1990s, from 0.6 g/bhp-hr in 1990 to 0.25 g/bhp-hr in 1991-1993, and 0.10 for 1994 and thereafter (the California standard was further reduced to 0.07 g/bhp-hr from 1994-1995 and to 0.05 g/bhp-hr for 1996 and thereafter). Also, new federal standards for HDVs have been proposed for 2004 and thereafter, with the principle change being a new combined standard of 2.4 or 2.5 g/bhp-hr for NO_x plus NMHCs (EPA, 1997).

Table 1: Federal and California Emission Standards for HDVs

HDV Standard	**CO**	**HCs**	**NO_x**	**PM**
Federal 1998+:				
g/bhp-hr	15.5	1.3	4.0	0.10
g/mi[a]	66.7	5.6	17.2	0.43
Proposed Federal 2004+:				
g/bhp-hr	15.5	2.4 or 2.5 NMHC+NO_x		0.10

g/mi[a]	66.7	10.3 or 10.8 NMHC+NO_x		0.43
California 1996+:				
g/bhp-hr	15.5	1.3/1.2[b]	4.0	0.05
g/mi[a]	66.7	5.6/5.2	17.2	0.22

Source: U.S. EPA, 1997

Notes: CO = carbon monoxide; HCs = hydrocarbons; NMHCs = non-methane hydrocarbons; NO_x = nitrogen oxides; PM = particulate matter.

[a] Emission standard values were converted from g/bhp-hr to g/mi with an approximate conversion factor of 4.3 bhp-hr/mile (CARB, 1996).

[b] 1.3 g/bhp-hr for total HCs and 1.2 g/bhp-hr for non-methane HCs (vehicles can certify to either standard).

Actual Emissions from Heavy-Duty Vehicles

In general, HDV diesel engines tend to easily meet the standards for CO and HCs, but they meet the standards for NO_x and PM with more difficulty. The less commonly used HDV gasoline engines emit lower levels of NO_x and PM than diesel engines, but higher levels of CO and HCs. Emission data for HDVs are generally more sparse than for LDVs, but engine certification data based on dynamometer testing, along with some data from chassis dynamometer testing, are available. For reference, Table A-1 (in Appendix A) presents heavy-HDV diesel engine data from CARB's 1999 engine certification listing.

Based on these certification data, and data from other sources, CARB has developed emission factors for HDVs for use in estimating the motor vehicle on-road emission inventory. The emissions inventories for mobile sources in California, for HDVs as well as other vehicle types, are estimated using the Motor Vehicle Emission Inventory (MVEI) family of models. The version of the model currently approved for use is MVEI7G, but a revised version of the model, EMFAC2000, has been proposed and is currently under review. This new version of the model is believed to more accurately represent actual in-use emissions from vehicles than previous model versions, due to a host of revised parameters, assumptions, and methodologies. Even this heavily-revised model probably does not estimate motor vehicle emissions with complete accuracy, but there is no readily-available better tool with which to analyze vehicle emissions in California. At any rate, it is clear from the large and in some cases dramatic increases in emissions estimated by EMFAC2000 relative to MVEI7G that considerable progress has been made with this latest model revision.

In order to illustrate the potential changes in emission factors for HDVs that will accompany the adoption of EMFAC2000 (if and when it is officially adopted), Table 2 presents estimated emission factors for various model years of diesel heavy-HDVs, for vehicles with 391,000 miles of use and that are mid-way between engine rebuilds.

Shown are the emission factors used in both MVEI7G and EMFAC2000 for purposes of comparison, for trucks of recent and future vintages. Also shown, for comparison, are the average values of the engine certification data presented in Table A-1, converted into units of grams per mile using an approximate conversion factor of 4.3 bhp-hr per mile.

Table 2: MVEI/EMFAC Model Emission Factors for Diesel Heavy-Heavy Duty Trucks with 391,000 Miles of Use (g/mi)

Model Version and Modeling Year	CO	HCs	NO_x	PM_{10}
1996-1997:				
MVEI7G	14.002	1.217	12.161	0.344
EMFAC2000	4.452	0.973	21.998	0.791
1998-2001:				
MVEI7G	14.002	1.217	9.729	0.344
EMFAC2000	4.452	0.973	17.598	0.791
2002-2003:				
MVEI7G	14.002	1.217	9.729	0.344
EMFAC2000	4.452	0.973	8.799	0.791
2004+:				
MVEI7G	14.002	1.217	9.729	0.344
EMFAC2000	4.452	0.404	8.799	0.791
Average of 1999 Engine Emissions Certification Data (from Table A-1)[a]	4.21	0.86	16.17	0.361

Source: CARB, 1999a

Notes: CO = carbon monoxide; HCs = hydrocarbons; NO_x = nitrogen oxides; PM_{10} = particulate matter ten microns or less in diameter.

[a] Converted from g/bhp-hr to g/mi using a conversion factor of 4.3 bhp-hr per mile.

In relation to MVEI7G, the HDV emissions estimation methodology used in EMFAC2000 is quite different. Whereas MVEI7G uses emission factors in units of grams per brake horsepower-hour (bhp-hr), derived primarily from engine dynamometer testing, the development of emission factors for EMFAC2000 drew upon emission data from chassis dynamometer testing and are in units of grams per mile. The chassis dynamometer data used to develop the EMFAC2000 emission factors were from testing of 17 trucks at the National Renewable Energy Laboratory. This change in methodology means that the emissions factors in EMFAC2000 have not been converted from units of grams per bhp-hr to units of grams per mile using conversion factors for bhp-hr per mile. Thus, one potential source of introducing inaccuracies into the estimates has been eliminated. EMFAC2000 emission factors also include revised estimates of idling emissions, and "off-cycle" NO_x emissions. The results of these latest revisions to the MVEI/EMFAC model are significant increases in estimated emissions of NO_x in pre-2002 modeling years and PM, slight decreases in estimated emissions of NO_x in 2002 and later modeling years, and significant decreases in estimated emissions of CO and HCs (CARB, 1999a).

Finally, Table 3 presents statewide average emission factors for medium and heavy HDTs, based on model runs of EMFAC2000. Presented in the table are results for three model years (2001, 2003, and 2010). These emission factors were calculated from the statewide total emissions in units of tons per day, using estimates of vehicle miles traveled (VMT) and a grams-per-ton conversion factor. As is evident in the table, heavy HDTs are modeled to emit higher grams-per-mile rates of CO, NO_x, and PM_{10} than medium HDTs, while medium HDTs emit higher rates of HCs. The higher emission rates of HCs for medium HDTs are due to the fact that a higher proportion of medium HDTs are gasoline powered, and gasoline powered heavy-duty engines tend emit more HCs than heavy duty diesel engines.

Table 3: EMFAC Model Average Emission Factors for Medium Heavy-Duty and Heavy Heavy-Duty Trucks (g/mi)

Modeling Year	**CO**	**HCs**	**NO_x**	**PM_{10}[a]**
2001:				
Medium HDTs	25.687	2.565	17.801	0.7375
Heavy HDTs	36.046	2.209	24.594	1.1990
Average	32.137	2.343	22.031	1.0249
2003:				
Medium HDTs	19.855	2.300	14.960	0.5071
Heavy HDTs	24.837	1.816	20.051	0.9056
Average	22.965	1.998	18.138	0.7559
2010:				
Medium HDTs	12.268	1.966	10.260	0.3122
Heavy HDTs	7.941	1.169	11.096	0.5150
Average	9.420	1.442	10.810	0.4457

Source: EMFAC2000 (v1.99) model runs for California statewide total emissions.
Notes: CO = carbon monoxide; HCs = hydrocarbons; HDTs = heavy-duty trucks; NO_x = nitrogen oxides; PCs = passenger cars; PM_{10} = particulate matter ten microns or less in diameter. Medium HDTs are trucks with a weight class of 14,001 to 33,000 pounds, and heavy HDTs are trucks with a weight class of 33,001 to 60,000 pounds.

[a] Includes running, idling, and starting emissions only. Excludes PM_{10} emissions from tire and brake wear because electric-drive HDTs would also emit particulates from these sources.

Pollutant Emissions from LDVs

The emissions from LDVs are also estimated in MVEI7G and EMFAC2000 using a similar emission-factor approach as is used for HDVs. The following table presents California statewide emission estimates from passenger cars and light-duty trucks (of 3,750 pounds or less), based on recent runs of the EMFAC2000 model. These emission estimates are emission factors, in units of grams per mile, that include running emissions, idling emissions, evaporative emissions (for hydrocarbons), and "cold start" emissions. The emission estimates were derived by running the EMFAC2000 model for a particular modeling year, in order to obtain a total emissions inventory for LDVs for each pollutant (in units of tons per day), and then back-calculating average gram-per-mile emission estimates. These gram-per-mile emission estimates were calculated using vehicle miles traveled (VMT) data and a grams-per-ton conversion factor. Shown in the table are emission factors for passenger cars, light-duty trucks, and a calculated average for LDVs in general.

Table 4: EMFAC Model Average Emission Factors for Light-Duty Vehicles (g/mi)

Modeling Year	CO	HCs	NO_x	PM_{10}[a]
2001:				
PCs	15.108	1.572	0.721	0.0142
LDTs	30.711	2.493	1.270	0.0228
LDV Average	17.656	1.722	0.810	0.0156
2003:				
PCs	11.355	1.203	0.533	0.0130
LDTs	23.115	1.898	0.951	0.0210
LDV Average	13.309	1.318	0.603	0.0143
2010:				
PCs	5.853	0.669	0.241	0.012
LDTs	11.501	0.955	0.439	0.018

LDV Average	6.842	0.719	0.275	0.013

Source: EMFAC2000 (v1.99) model runs for California statewide total emissions.
Notes: CO = carbon monoxide; HCs = hydrocarbons; LDTs = light-duty trucks of 3,750 pounds or less; NO_x = nitrogen oxides; PCs = passenger cars; PM_{10} = particulate matter ten microns or less in diameter.
[a]Includes running, idling, and starting emissions only. Excludes PM_{10} emissions from tire and brake wear because electric-drive HDTs would also emit particulates from these sources.

Potential ZEV Credit Schemes for Zero-Emission Heavy-Duty Trucks

The California ZEV mandate is based on the premise that the production and use of vehicles with no tailpipe emissions can lead to overall reductions in criteria pollutant emissions. This is because the emissions associated with producing electricity to recharge battery EVs (or in principle with producing hydrogen for direct-hydrogen fuel cell vehicles – the other currently known ZEV type) are much lower than the tailpipe emissions of conventional vehicles. In support of this premise, several studies on the potential emissions associated with battery EV recharging have shown that EVs used in California would have much lower associated pollutant emissions than conventional vehicles. The consensus of these studies is that CO and HC emissions would be nearly eliminated if battery EVs were used in place of conventional vehicles, and NO_x and PM emissions would be significantly reduced (Dowlatabadi, et al., 1990; Yau et al., 1993; Hwang et al., 1994, CARB, 1996, Acurex, 1996a, Rau et al., 1996, Wang et al., 1990; Austin and Caretto, 1995). Furthermore, the location of the emissions would change such that fewer emissions would occur in crowded urban areas where they tend to have the greatest negative impact.

Given their relatively high emissions, particularly of NO_x and PM, HDTs are attractive targets for ZEV technology. In general, however, HDTs have tended to receive less attention than LDVs as potential ZEVs, and at present the California ZEV mandate applies only to manufacturers of LDVs. Therefore, only production of light-duty ZEVs can lead to the award of ZEV credits, and there is therefore no regulatory pressure or incentive for manufacturers of HDTs to produce vehicles that employ ZEV technology.

Methods for Estimating ZEV Credits for HDTs

One basic method that can be used to estimate the appropriate number of ZEV credits to award to manufacturers of HDTs is to estimate the relative level of emissions of each pollutant from HDTs and LDVs, and to multiply the resulting emission factor ratio by the average annual mileage ratio of HDTs and LDVs. This results in a relative estimate of the overall emission benefit of replacing typical LDVs and HDTs with their zero-emission counterparts.

In order to arrive at an overall estimate of the number of ZEV credits to be awarded, across all four pollutants of concern, values for each pollutant can be weighted by the approximate relative damages caused by each pollutant in order to arrive at a weighted average result. Alternately, a simple average can be calculated with the underlying assumption that each pollutant "counts the same."

With regard to the damage value weighted-average approach, there is an extensive literature on damage and control costs of different pollutants in various regions of California and the U.S. These various estimates of the relative benefits of reducing different pollutants can be the basis for such a pollutant-weighting scheme. For example, Table 5 presents several estimates for damage and control costs of different pollutants in different regions.

Table 5: Damage and Control Cost Values for Criteria Pollutants ($/ton per year)

Source/Location	Type	HC	CO	NO_x	PM_{10}	SO_x
CEC (1992) South Coast (1989$s)	Damage	6,911	3	14,483	47,620	7,425
	Control	18,900	9,300	26,400	5,500	19,800
CEC (1992) Ventura County (1989$s)	Damage	286	0	1,647	4,108	286
	Control	21,100	I.A.	16,500	1,800	21,100
CEC (1992) Bay Area (1989$s)	Damage	90	1	7,345	24,398	90
	Control	10,200	2,200	10,400	2,600	10,200
CEC (1992) San Diego (1989$s)	Damage	98	1	5,559	14,228	98
	Control	17,500	1,100	18,300	1,000	17,500
CEC (1992) San Joaquin Valley (1989$s)	Damage	3,711	0	6,473	3,762	3,711
	Control	9,100	3,200	9,100	5,200	9,100
CEC (1992) Sacramento Valley (1989$s)	Damage	90	1	7,345	24,398	4,129
	Control	9,100	5,000	9,100	2,800	9,100
CEC (1992) North Coast (1989$s)	Damage	467	0	791	551	467
	Control	3,500	I.A.	6,000	900	3,500
CEC (1992) N. Central Coast (1989$s)	Damage	803	0	1,959	2,867	803
	Control	9,100	I.A.	9,100	900	9,100
CEC (1992) S. Central Coast (1989$s)	Damage	286	0	1,647	4,108	286
	Control	9,100	I.A.	9,100	900	9,100
CEC (1992) Southwest Desert (1989$s)	Damage	157	0	439	680	157
	Control	3,500	2,900	6,000	5,700	3,500
ECO Northwest (1987) – W. Oregon[a] (1989$s)	Damage	N.E.	N.E.	839	1950	N.E.
EIA (1995) – Nevada[b] (1992$s)	Control	1,012	1,012	7,480	4,598	1,716
EIA (1995) - Oregon[b] (1992$s)	Control	N.E.	N.E.	3,500	3,000	0
EIA (1997) – CAAA, Title IV[c]	Control	N.E.	N.E.	N.E.	N.E.	113-322
McCubbin and Delucchi (1996) – Los Angeles[d] (1991$s)	Damage	472 – 3,892	27 - 163	5,933 - 70,515	11,204 - 141,140	30,418 - 190,400
McCubbin and Delucchi (1996) – United States[d] (1991$s)	Damage	91 – 898	9 - 82	998 - 14,705	544 - 13,726	2,540 - 20,502
PG&E – CA facilities[e] (1996$s)	Control	4,236	N.E.	9,120	2,624	4,486
PG&E – Pacific NW[e] (1996$s)	Control	0	N.E.	292	556	298
SCE – CA facilities[e] (1992$s)	Control	22,462	N.E.	31,448	6,804	23,490
Small and Kazimi (1995) – South Coast (1992$s)	Damage	2,920	N.E.	10,670	N.E.	109,900
Wang and Santini (1994) - Chicago[f] (1994$s)	Damage	2,700	N.E.	5,380	10,840	3,600
	Control	8,150	2,440	7,990	4,660	9,120
Wang and Santini (1994) – Houston[f] (1994$s)	Damage	3,540	N.E.	6,890	5,190	2,910
	Control	15,160	2,680	17,150	2,780	3,590

Notes: CAAA = Clean Air Act Amendments of 1990: CO = carbon monoxide; HC = hydrocarbon; I.A. = district is in attainment; N.E. = not estimated; NO_x = oxides of nitrogen; PG&E = Pacific Gas and Electric; PM_{10} = particulate matter less than 10 microns in diameter; SCE = Southern California Edison; SO_x = oxides of sulfur. CEC (1992) values are from EIA (1995).

[a] These values are reported in Wang and Santini (1994).

[b] These values were adopted by the states for use in state utility planning decisions.

[c] These values are based on experience by eastern and mid-western state utilities in meeting CAAA Title IV SO_x regulations. The $322 per ton control cost is for using scrubbers, and the $113 per ton control cost is for modifying a plant to burn lower sulfur coal.

[d] These values were estimated by assuming a 10% decrease in motor vehicle emissions, and then estimating the resulting change in ambient air quality and reduction in damages. The values shown are the results when upstream emissions and road dust are included. The authors also calculate results excluding these emission sources, and the resulting damage values are higher than the ones shown. Values were converted from $/kg to $/ton using 907.2 kg/ton.

[e] These values, documented in EIA (1995) are used by the utility in planning decisions for the region shown.

[f] These values were estimated through regression analysis of pollutant concentration and population levels in the region.

Thus, one possible method for considering the relative value of reducing emissions of all four pollutants of concern from motor vehicles would be to weight the pollutants based on their approximate damage values. If the damage values from the CEC (1992) study (reported in EIA [1995]) were considered for the most likely areas for ZEVs to be introduced, then the weighting values shown in Tables 6 and 7 would result. These pollutant weights are normalized to the damage values for HCs, and they are averages of the damage values for the South Coast, Ventura County, the Bay Area, and the Sacramento Valley.[6] These values are used because they are a disaggregated set of factors for areas in which ZEVs would be likely to be used, and they are the most complete estimates for which precise answers are provided. McCubbin and Delucchi's (1996) estimates are more up to date, their broad ranges of uncertainty make calculating ratios between pollutants difficult. In time, when the recent epidemiology of air toxics that has continued to demonstrate the harm caused by fine particulate is integrated into the damage value calculations, the estimated value of particulate harm is certain to increase, toward McCubbin and Delucchi's (1996) high case values. In this case, the damages would be even more heavily weighted toward the damages of PM, further increasing the number of ZEV credits for zero-emission HDTs. Hence, these estiamates are somewhat conservative in this regard.

Table 6 presents a series of the calculations described above for medium HDTs (with vehicle weights between 14,001 and 33,000 pounds), again based on EMFAC2000

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[6] The damage values could be further weighted by population levels in the various regions, but this would be unlikely to significantly change the results because they are relative damage values, rather than absolute values.

emission model data, for three different emission modeling years. Table 7 presents a similar analysis for heavy HDTs, with vehicle weights of 33,001 pounds to 60,000 pounds.

Table 5: Potential ZEV Credits for Zero-Emission Medium HDTs

Modeling Year and Pollutant	Emission Factor Ratio (MHDT/LDV)	Avg. Annual Mileage Ratio (MHDT/LDV)	Pollutant Damage Weight	HDT ZEV Credits
2001:				
CO	1.45	1.45	0.0	0.0
HCs	1.49	1.45	1.0	2.2
NO_x	21.97	1.45	4.2	133.8
PM_{10}	47.32	1.45	13.6	933.2
Weighted Avg.				**57**
CO	1.45	1.45	1.0	2.1
HCs	1.49	1.45	1.0	2.2
NO_x	21.97	1.45	1.0	31.9
PM_{10}	47.32	1.45	1.0	68.6
Simple Avg.				**26**
2003:				
CO	1.49	1.53	0.0	0.0
HCs	1.74	1.53	1.0	2.7
NO_x	24.82	1.53	4.2	159.5
PM_{10}	35.37	1.53	13.6	736.0
Weighted Avg.				**48**
CO	1.49	1.53	1.0	2.3
HCs	1.74	1.53	1.0	2.7
NO_x	24.82	1.53	1.0	38.0
PM_{10}	35.37	1.53	1.0	54.1
Simple Avg.				**24**
2010:				
CO	1.79	1.64	0.0	0.0
HCs	2.73	1.64	1.0	4.5
NO_x	37.26	1.64	4.2	256.6
PM_{10}	24.03	1.64	13.6	536.0
Weighted Avg.				**42**
CO	1.79	1.64	1.0	0.0
HCs	2.73	1.64	1.0	2.9
NO_x	37.26	1.64	1.0	61.1
PM_{10}	24.03	1.64	1.0	39.4

Simple Avg.				**26**

Notes: CO = carbon monoxide; HCs = hydrocarbons; HDT = heavy-duty truck; LDV = light-duty vehicle (includes passenger cars and light-duty trucks of 3,750 pounds or less); MHDT = medium HDT; NO_x = nitrogen oxides; PM_{10} = particulate matter ten microns or less in diameter; ZEV = zero-emission vehicle.

Table 5: Potential ZEV Credits for Zero-Emission Heavy HDTs

Modeling Year and Pollutant	Emission Factor Ratio (HHDT/LDV)	Avg. Annual Mileage Ratio (HHDT/LDV)	Pollutant Damage Weight	HDT ZEV Credits
2001:				
CO	2.04	3.62	0.0	0.0
HCs	1.28	3.62	1.0	4.6
NO_x	30.35	3.62	4.2	461.4
PM_{10}	76.92	3.62	13.6	3,786.9
Weighted Avg.				**226**
CO	2.04	3.62	1.0	7.4
HCs	1.28	3.62	1.0	4.6
NO_x	30.35	3.62	1.0	109.9
PM_{10}	76.92	3.62	1.0	278.5
Simple Avg.				**100**
2003:				
CO	1.87	3.85	0.0	0.0
HCs	1.38	3.85	1.0	5.3
NO_x	33.27	3.85	4.2	538.0
PM_{10}	63.15	3.85	13.6	3,306.5
Weighted Avg.				**205**
CO	1.87	3.85	1.0	7.2
HCs	1.38	3.85	1.0	5.3
NO_x	33.27	3.85	1.0	128.1
PM_{10}	63.15	3.85	1.0	243.1
Simple Avg.				**96**
2010:				
CO	1.16	4.79	0.0	0.0
HCs	1.63	4.79	1.0	7.8
NO_x	40.30	4.79	4.2	810.8
PM_{10}	39.64	4.79	13.6	2,582.3
Weighted Avg.				**181**
CO	1.16	4.79	1.0	5.6
HCs	1.63	4.79	1.0	7.8
NO_x	40.30	4.79	1.0	193.0
PM_{10}	39.64	4.79	1.0	189.9

Simple Avg.				**99**

Notes: CO = carbon monoxide; HCs = hydrocarbons; HDT = heavy-duty truck; HHDT = heavy HDT; LDV = light-duty vehicle (includes passenger cars and light-duty trucks of 3,750 pounds or less); NO_x = nitrogen oxides; PM_{10} = particulate matter ten microns or less in diameter; ZEV = zero-emission vehicle.

Conclusions and Policy Recommendations

This report has analyzed the average relative emission levels of CO, HCs, NO_x, and PM_{10} from LDVs and HDTs in California, as estimated in the latest version of the CARB mobile source emission inventory model, EMFAC2000. Using these estimates of the relative emission reduction potential of zero-emission LDVs and medium and heavy HDTs, along with estimates of the average annual mileage for these vehicle classes, potential ZEV credit award levels for zero-emission HDTs have been estimated.

The findings are that from 42 to 226 ZEV credits could in principle be justified to be awarded to manufacturers of zero-emission HDTs, depending on the model year of their introduction (from 2001 to 2010) and the HDT weight class, if the four pollutants are weighted according to their approximate relative damage values. These damage values reflect the impact on each pollutant to human health in major California urban areas. Using a simpler scheme that does not consider the relative damages from the pollutants, and that weights each pollutant equally, potential ZEV credit award levels range from 24 to 100 credits for zero-emission HDTs.

This analysis has been conducted because under the upcoming biennial review of the ZEV mandate, CARB may wish to consider broadening the mandate to allow ZEV credits to be awarded to manufacturers of HDTs, in order to address the pressing problem of diesel engine emissions in California. Diesel engines contribute a disproportionate amount of NO_x and PM_{10} pollution to the state's emission inventory, and PM_{10} emissions in particular are increasingly seen as having the most serious health effects of all vehicle pollutants. Recent monitoring studies have shown that ambient concentrations of PM_{10} are in some cases much higher than the estimated statewide averages, and also that in some areas of the South Coast Air Basin emissions from diesel engines account for up to 70% of the total carcinogenic risk from air toxic contaminants.

Given the magnitude and importance of diesel emissions in California, and that the goal of the ZEV mandate is to reduce emissions and accelerate the development and commercialization of inherently low-emitting technologies, it makes sense to include HDVs in the mandate in some way. Unlike in the urban bus class of HDVs, however, where CARB has recently imposed zero-emission bus regulations that complement the ZEV mandate regulations that apply to LDV manufacturers, purchases of HDTs are not heavily subsidized by public funding sources. Therefore, it would be much less feasible to require initially costly ZEV technology for HDTs, and to impose additional costs on the HDT industry (which is characterized by intense competition and razor-thin profit margins).

Rather, manufacturers of HDTs who choose to build zero-emission HDTs that then are introduced into California-based fleets could be awarded ZEV credits that could subsequently be marketed to the LDV manufacturers that are bound by the mandate. This would build additional flexibility into the mandate, without sacrificing any of its emission-reduction goals. Particularly in the early years of the ZEV mandate, when fuel cell technology is likely to be at too early a stage of development to introduce into LDV fleets in large numbers, this additional flexibility could allow LDV manufacturers to meet their ZEV mandate requirements in a more cost-effective manner than the alternative of producing battery-electric vehicles.

As a final point, as it considers the potential adoption of a ZEV credit scheme for HDTs similar to the one outlined in this report, CARB may also wish to consider that certain zero-emission HDT technologies may have the potential to aid in the commercialization of zero-emission LDVs. This is possible because the introduction of some types of zero-emission HDTs could promote the development of refueling infrastructure that would be suitable for both LDVs and HDTs. This type of "spillover" effect could aid in the successful commercialization of zero-emission LDVs, and potentially enhance the emission reduction benefits of the ZEV program.

For example, one type of zero-emission HDT technology would use an on-board electrolyzer to produce hydrogen from water and electricity, that then would be used in a fuel cell/electric motor drive system. Since these vehicles would not need to refuel with off-board hydrogen, a major infrastructure hurdle would be eliminated. This same electrolyzer technology could also be well-suited for light-duty ZEVs that use fuel cells, and if the costs of the electrolyzers and associated water and electricity refueling ports were driven down by first being used in HDTs, the feasibility of having widespread use of direct-hydrogen fuel cell LDVs could be enhanced. CARB may thus wish to consider the possibility of encouraging this type of synergistic technology development, with spillover benefits between the HDT and LDV sectors, by particularly encouraging zero-emission HDT technologies that offer these types of potential benefits. This could be done by offering a ZEV credit premium to zero-emission HDTs that use refueling infrastructure that also would be suitable for light-duty ZEVs, under the assumption that cost reductions from the development of infrastructure for HDTs would subsequently aid in the development of such infrastructure for LDVs. This could therefore enhance the commercialization potential of light-duty ZEVs, and help to remove a major barrier to widespread ZEV use.

References

Acurex Environmental Corporation, *Evaluation of Fuel-Cycle Emissions on a Reactivity Basis: Volume 1 - Main Report*, FR-96-114, Prepared for California Air Resources Board, Mountain View, September 19, 1996.

T.C. Austin and L.C. Caretto, "Powerplant Emissions and Energy Consumption Associated with Electric Vehicle Recharging," 5th CRC On-Road Vehicle Emissions Workshop, April 3, 1995.

California Air Resources Board (CARB), "Proposed Amendments to the Low-Emission Vehicle Regulations to Add an Equivalent Zero-Emission Vehicle Standard," Preliminary Draft Staff Report, Mobile Source Division, El Monte, California, June 11, 1996.

California Air Resources Board (CARB), "Proposed California Zero-Emission and Hybrid Electric Vehicle Exhaust Emission Standards and Test Procedures for 2003 and Subsequent Model Passenger Cars, Light-Duty Trucks and Medium-Duty Vehicles," Sacramento, California, September 18, 1998a.

California Air Resources Board (CARB), "1998 Zero-Emission Vehicle Biennial Program Review," California Environmental Protection Agency, Sacramento, California, July 6, 1998b.

California Air Resources Board (CARB), "The Toxic Air Contaminant Identification Process: Toxic Air Contaminant Emissions from Diesel-fueled Engines (Fact Sheet),"Sacramento, California, October, 1998c.

California Air Resources Board (CARB), "EMFAC 2000 On-Road Emissions Inventory Estimation Model Technical Support Document,"Sacramento, California, October, 1999a.

California Air Resources Board (CARB), "1999 Model Year Heavy-Duty On-Road Engine Certification Listing Update," El Monte, California, 1999b.

S.C. Davis, *Transportation Energy Data Book: Edition 17*, ORNL-6919, Office of Transportation Technologies, U.S. Department of Transportation, Washington, D.C., August, 1997.

S.C. Davis, *Transportation Energy Data Book: Edition 19*, ORNL-6919, Office of Transportation Technologies, U.S. Department of Transportation, Washington, D.C., August, 1999.

Energy Information Administation (EIA), *Electricity Generation and Environmental Externalities: Case Studies*, DOE/EIA - 0598, Energy Information Administration Office of Coal, Nuclear, Electric, and Alternate Fuels, U.S. Department of Energy, Washington, D. C., September, 1995.

H. Dowlatabadi, A.J. Krupnick, and A. Russell, "Electric Vehicles and the Environment: Consequences for Emissions and Air Quality in Los Angeles and U. S. Regions," Discussion Paper, QE91-01, Resources for the Future, Washington, D. C., October, 1990.

Health Effects Institute (HEI), "Program Summary: Research on Diesel Exhaust,"December, 1999.

R. Hwang, M. Miller, A.B. Thorpe, and D. Lew, *Driving Out Pollution: The Benefits of Electric Vehicles*, Union of Concerned Scientists, Berkeley, November, 1994.

D.R. McCubbin and M.A. Delucchi, *The Social Cost of The Health Effects of Motor Vehicle Air Pollution*, UCD-ITS-RR-96-3 (11), Institute of Transportation Studies - Davis, Davis, August, 1996.

N.S. Rau, S.T. Adelman, and D.M. Kline, *EVTECA - Utility Analysis Volume 1: Utility Dispatch and Emissions Simulations*, TP-462-7899, National Renewable Energy Laboratory, Golden, 1996.

South Coast Air Quality Management District (SCAQMD), *Multiple Air Toxics Exposure Study – MATES II (Draft)*, November 9, 1999.

K. Small and C. Kazimi, "On the costs of air pollution from motor vehicles," *Journal of Transportation Economic Policy* **29**: 7-32, 1995.

G.M. Solomon, T.R. Campbell, T. Carmichael, G. Ruderman Feuer, and J.S. Hathaway, "Exhausted by Diesel: How America's Dependence on Diesel Engines Threatens Our Health," Natural Resources Defense Council (NRDC), April, 1998.

U.S. Department of Commerce (U.S. DOC), "1992 Census of Transportation: Truck Inventory and Use Survey," TC92-T-52, May, 1995.

U.S. Environmental Protection Agency (U.S. EPA), “National Air Pollutant Emission Trends, 1900-1995,” Office of Air Quality, EPA454/R-96-007, September, 1996.

U.S. Environmental Protection Agency (U.S. EPA), “Emission Standards Reference Guide for Heavy-Duty and Nonroad Engines,” Air and Radiation Division, EPA420-F-97-014, September, 1997.

Q. Wang et al., "Emissions Impacts of Electric Vehicles," Journal of the Air and Waste Management Association 40: 1275-1284, 1990.

M.Q. Wang and D.J. Santini, "Monetary Values of Air Pollutant Emissions in Various U.S. Regions," *Transportation Research Record* **1475**: 33-41, 1994.

T.S. Yau, H.W. Zaininger, M.J. Bernard, M.K. Singh, and C.L. Saricks, *Utility Emissions Associated with Electric and Hybrid Vehicle Charging,* DOE/CE-0395, Office of Transportation Technologies, U.S. Department of Energy, Washington, D.C., April, 1993.

Appendix A

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Table A-1: 1999 CARB Diesel Engine Emissions Certification Data (Heavy-Heavy Duty Vehicle Engines)

Manufacturer	**Engine Type**	**Displacement (liters)**	**HCs (g/bhp-hr)**	**CO (g/bhp-hr)**	**NOx (g/bhp-hr)**	**PM (g/bhp-hr)**
Caterpillar	XCPXH0629ERK	10.3	0.21	1.11	3.7	0.079
Caterpillar	XCPXH0729ERK	12	0.24	0.96	3.6	0.073
Caterpillar	WCPXH0893ERK	N.R.	0.2	1.39	3.8	0.075
Caterpillar	XCPXH0967ERK	15.8	0.13	1.16	3.8	0.08
Cummins	XCEXH0661MAH	10.8	0.2	0.9	3.7	0.08
Cummins	XCEXH0661MAI	10.8	0.26	0.87	3.77	0.082
Cummins	XCEXH0855NAD	14	0.4	1	3.82	0.093
Cummins	XCEXH0855NAE	14	0.4	0.8	3.8	0.086
Cummins	XCEXH0855NAF	14	0.4	0.8	3.22	0.093
Cummins	XCEXH0912XAB	14.9	0.14	0.78	4.03	0.08
Cummins	XCEXH0912XAD	14.9	0.1	0.4	3.6	0.08
DDC	XDDXH08.5EJL	8.5	0.1	1	3.8	0.101
DDC	XDDXH11.1EHL	11.1	0.1	1.38	3.9	0.09
DDC	XDDXH12.7EGL	12.7	0.1	0.7	3.9	0.1
Mack	XMKXH11.9E54	11.9	0.2	N.R.	3.8	0.074
Volvo	XVTXH07.350S	7.3	0.1	1	3.7	0.1
Volvo	XVTXH12.150S	12.1	0.1	1.5	4	0.06
Average Values		**12.2**	**0.20**	**0.98**	**3.76**	**0.084**

Source: CARB, 1999b

Notes: CO = carbon monoxide; HCs = hydrocarbons; NOx = nitrogen oxides; N.R. = not reported; PM = particulate matter.