Reducing Greenhouse Gas Emissions from Light-Duty Motor Vehicles

Prepared by

NESCCAF
Northeast States Center for a Clean Air Future

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Executive Summary

ES-1. Overview

This study provides an assessment of the greenhouse gas (GHG) emissions reductions that could be achieved in new, light-duty motor vehicles through the application of currently available and advanced motor vehicle technologies in the 2009-2015 timeframe. Results were obtained from original cost and technology analyses conducted for this study, together with information obtained from other available reports.

Relative to other sectors of the economy, motor vehicles account for a particularly large share – 20 to 25 percent – of total anthropogenic GHG emissions in the Northeast. Because total vehicle miles traveled are predicted to rise steadily in coming decades, motor vehicles also represent the fastest growing portion of the region's overall GHG inventory. As such, the Northeast states – all of which, individually or as a region, are committed to reducing emissions that contribute to the risk of future climate change – have a keen interest in addressing the emissions contribution of the light-duty vehicle fleet. Further impetus for this assessment comes from California's recent action – as required by Assembly Bill 1493 – to develop regulations aimed at achieving maximum feasible and cost-effective reductions in GHG emissions from light-duty vehicles beginning in model year 2009.

In recent years, numerous technologies that could substantially reduce motor vehicle GHG emissions have been developed and brought into production. For the most part, however, recent technology advances have been used to boost vehicle performance rather than to reduce emissions. With more aggressive deployment of these technologies and greater emphasis on their application in ways that reduce emissions, this study finds that average GHG emissions from new vehicles could be substantially reduced over the next decade.

The report has four sections: Chapter 1 provides background information on the rationale for reducing passenger car GHG emissions and discusses the regulatory context for such efforts. Chapter 2 describes the methodology used to assess emissions reduction potential and cost for various motor vehicle technologies. Chapter 3 presents the results of this analysis. Finally, several technical appendices attached to this report provide additional information on the methodology, assumptions, and information sources used in this study. The following sections provide an overview of each chapter.

ES-2. Methodology

The core of the analysis consisted of a series of modeled simulations to predict the emissions impacts of incorporating various technology combinations in new vehicles. Simulations were performed for five classes of vehicles (small car, large car, minivan, small truck, and large truck) using AVL Powertrain Engineering, Inc.'s CRUISE software, which provides detailed information on the acceleration, braking, and emissions performance of different motor vehicle designs, including advanced powertrain designs.

A first step in the analysis was to develop baseline simulation models in each of the five vehicle classes studied (using average or predominant vehicle characteristics in each class), together with a list of GHG-reducing technologies. Based on an initial estimate of the emissions reduction potential of each individual technology, packages of technologies were selected for detailed evaluation. Simulation modeling was then performed to assess the combined emissions impacts of these technology packages. The only exception to the simulation modeling approach was for hybrid electric vehicles, which were evaluated using available vehicle certification data. Final steps in the analysis involved estimating the cost of each package and creating technology cost curves based on the simulation results. Detailed cost estimates were developed by the Martec Group, Inc. using industry information gathered from interviews and technical papers. (Wherever possible, Martec sought to obtain input from two or more automakers and two or more suppliers for each technology evaluated.) The component costs estimated by Martec were converted into equivalent retail prices (RPE) using a standard markup factor. Net cost-effectiveness was evaluated by comparing the estimated retail price equivalent of the incremental vehicle system and component hardware costs associated with different technology packages to fuel cost savings over the life of the vehicle. Finally, separate technology assessments were conducted by Meszler Engineering Services to assess the GHG-reduction impacts associated with air conditioning systems, as well as methane and nitrous oxide emissions.

ES-3. Results

Chapter 3 details results for the five classes of vehicles evaluated in this study. These results indicate that substantial, cost-effective GHG emission reductions are achievable for light duty vehicles in the 2009 to 2015 timeframe. Specifically, this analysis showed that emissions in each of the five vehicle classes could generally be reduced by approximately 14 to 54 percent, relative to 2002 baseline vehicles.

Similar technology packages were evaluated for each of the five classes of vehicles. The simulation results indicate that each of these packages achieve comparable CO_2 reductions across all vehicle classes analyzed. For example, the technology package including stoichiometric gasoline direct injection, cam phaser, turbocharging, and automated manual transmission technology was evaluated for four classes of vehicles. In each class, estimated emissions reductions achieved by this particular technology combination were between 27 and 30 percent relative to the baseline vehicle.[1] The largest number of technology packages was evaluated for the large car category. While some of these technology combinations were not evaluated for vehicle classes other than large cars, the consistency of results across vehicle classes suggests that similar CO_2 reductions would likely be achieved with the deployment of the same technology packages in other classes.

Because estimated emissions reductions for all five vehicle classes were comparable, detailed results are described here only for the large car class. Results for the other four classes are reviewed briefly after the discussion of large car results; additional detail concerning the other four categories of vehicles can be found in Chapter 3.

[1] There are some exceptions to this general finding; these are detailed in Chapter 3.

ES-3.1. Large Car Results

Table ES-1 presents emission reduction and cost estimates for the 19 technology packages modeled for the large car class. Column 1 lists the technologies included in each combination package. Column 2 provides the combined city/highway CO_2 emissions rate of the modeled package in grams per mile (g/mi). Column 3 lists the percent CO_2 reduction relative to the 2002 baseline technology package. Column 4 lists the estimated incremental vehicle cost associated with the addition of these technologies. Column 5 indicates the net cost of the technology package, defined as incremental technology cost minus lifetime fuel savings.[2] The net cost analysis assumes a price of $1.58 per gallon for both gasoline and diesel. Last, Column 6 shows net cost per avoided ton of CO_2 emissions. Note that a negative net cost means that fuel savings more than offset the incremental cost of the emissions reduction technologies being modeled. In other words, it equates to projected consumer savings over the lifetime of the vehicle.

As indicated by Table ES-1, estimated emission reductions range from 14-54 percent, relative to the 2002 baseline vehicle, for the 19 large car technology packages modeled. According to this analysis, combinations of technologies already used in some production gasoline models can reduce CO_2 emissions by approximately 25 percent. Examples of these technologies include 6-speed automatic transmissions, variable valve lift and timing, and cylinder deactivation. Reductions beyond this level will require the introduction of more advanced technologies such as gasoline direct injection, 42-volt starter generators, and diesel engine technology. For example, the combination of gasoline direct injection and 42-volt technology, along with turbocharging and advanced cam and transmission technology, can provide a 37 percent CO_2 reduction for an incremental vehicle cost of $1,700. Even greater CO_2 reductions can be achieved using hybrid-electric designs. It is critical to recognize that while the costs of using advanced technologies are somewhat greater than the cost of conventional gasoline technologies, fuel-cost savings over the life of the vehicle far outweigh additional technology costs in all but the most aggressive technology packages. On a dollar per ton basis, the net cost of technology packages that produce up to 47 percent CO_2 reductions is negative, meaning that these packages result in net cost savings over the lifetime of the vehicle.

As noted in Table ES-1, the emission reduction packages evaluated in this study include a wide range of individual technologies. Some of the most cost-effective packages include automated manual transmissions, turbocharging, stoichiometric gasoline direct injection, and camless valve actuation technology. Turbocharging, especially, proves to be a very cost-effective technology in the large car and other vehicle classes because it enables the manufacturer to downsize the vehicle engine and decrease engine cylinder count while maintaining equal performance. This study also assessed the GHG-reducing potential of technologies that are relatively expensive in an effort to provide a robust overview of the benefits and costs of candidate CO_2-reduction technologies. Given that future technology advances could reduce costs for these

[2] This analysis assumes the vehicle life to be 12 years and 150,000 miles. More detail on the analysis and assumptions are provided in Chapter 2 on methods.

Table ES-1: Large Car GHG Reduction Results for Combinations of Technologies

(1) Technology Combinations	(2) CO_2 (g/mi)	(3) CO_2 Change (percent)	(4) Marginal Vehicle Cost ($)	(5) Net Cost ($)	(6) Net Cost ($ per ton CO_2)
Dual Cam Phasers, 6-Speed Automatic Transmission	305.4	14.4%	479	-438	-52
Dual Cam Phasers, Continuously Variable Transmission, Electric Power Steering, Improved Alternator	304.4	14.6%	725	-217	-25
Discrete Variable Valve Lift, Dual Cam Phasers, 6-Speed Automatic Transmission	300.3	15.8%	640	-393	-42
Continuous Variable Valve Lift, Dual Cam Phasers, 6-Speed Automatic Transmission	291.4	18.3%	864	-358	-33
Dual Cam Phasers, Cylinder Deactivation, 6-Speed Automatic Transmission	288.1	19.2%	640	-642	-57
Dual Cam Phasers, Turbocharging, 6-Speed Automatic Transmission, Electric Power Steering, Improved Alternator	280.3	21.4%	73	-1,386	-110
Gasoline Homogeneous Charge Compression Ignition, Discrete Variable Valve Lift, Intake Cam Phasers, Automated Manual Transmission, Electric Power Steering, Improved Alternator	273.8	23.2%	1,149	-444	-32
Continuous Variable Valve Lift, Dual Cam Phasers, Automated Manual Transmission, Electric Power Steering, Improved Alternator	266.3	25.3%	890	-857	-57
Stoichiometric Gasoline Direct Injection, Cylinder Deactivation, Dual Cam Phasers, Automated Manual Transmission, Electric Power Steering, Improved Alternator	266.2	25.4%	925	-829	-55
Cylinder Deactivation, Discrete Variable Valve Lift, Coupled Cam Phasers, 6-Speed Automatic Transmission, 42 Volt Integrated Starter/Generator, Electric Power Steering, Electric Accessories	261.1	26.8%	2,432	554	35
Stoichiometric Gasoline Direct Injection, Dual Cam Phasers, Turbocharging, Automated Manual Transmission, Electric Power Steering, Improved Alternator	252.5	29.2%	176	-1,868	-109
Electrohydraulic Camless Valve Actuation, Automated Manual Transmission, Electric Power Steering, Improved Alternator	252.0	29.3%	1,219	-841	-49
Diesel Homogeneous Charge Compression Ignition, Automated Manual Transmission, 42 Volt Integrated Starter/Generator, Electric Power Steering, Electric Accessories	248.6	30.3%	2,780	-41	-2
Electrohydraulic Camless Valve Actuation, Stoichiometric Gasoline Direct Injection, Automated Manual Transmission, Electric Power Steering, Improved Alternator	243.4	31.8%	1,478	-759	-41
Gasoline Homogeneous Charge Compression Ignition, Discrete Variable Valve Lift, Intake Cam Phasers, Automated Manual Transmission, 42 Volt Integrated Starter/Generator, Electric Power Steering, Electric Accessories	232.8	34.7%	2,745	274	13
Stoichiometric Gasoline Direct Injection, Turbocharging, Dual Cam Phasers, 6-Speed Automatic Transmission, 42 Volt Integrated Starter/Generator, Electric Power Steering, Electric Accessories	225.3	36.8%	1,858	-775	-36
Motor Assist Gasoline Hybrid	189.9	46.7%	2,797	-609	-22
Fully Integrated Diesel Hybrid	163.0	54.3%	7,543	3,105	97
Fully Integrated Gasoline Hybrid	162.7	54.4%	5,387	1,391	43

technologies, the costs presented could be overstated. Consequently, the complete set of technology packages does not constitute a low-cost solution to any particular CO_2-reduction scenario, but rather presents a host of possible solutions across a range of reductions and costs.

Figure ES-2 graphically depicts the relative benefits and costs of each of the evaluated technology packages. As this figure suggests, the technology packages span a broad range of reduction potentials and costs. For example, packages providing CO_2 reductions from 14 to 30 percent (emissions between 300 and 250 g/mi CO_2) encompass a net cost range from approximately negative $1,900 (i.e., net consumer savings) to positive $500 (i.e., net consumer cost). Clearly, a least-cost solution would favor the technology packages in the lower end of this cost range. Nevertheless, for purposes of this study, we have assumed a technology supply curve[3] that includes all of the evaluated technology packages. This allows for the fact that least-cost technologies may not be viable for some segments of the market and that vehicle manufacturers may therefore choose not to implement specific CO_2-reduction solutions across the entire vehicle class. For example, because technologies such as automated manual transmissions and turbocharging may be limited to a subset of the models in any class of vehicles, a supply curve constructed solely on the basis of least-cost solutions may understate the actual cost of a class-wide CO_2-reduction solution. Including all of the evaluated technology packages in the development of the supply curve provides a more robust indication of likely class-wide impacts.

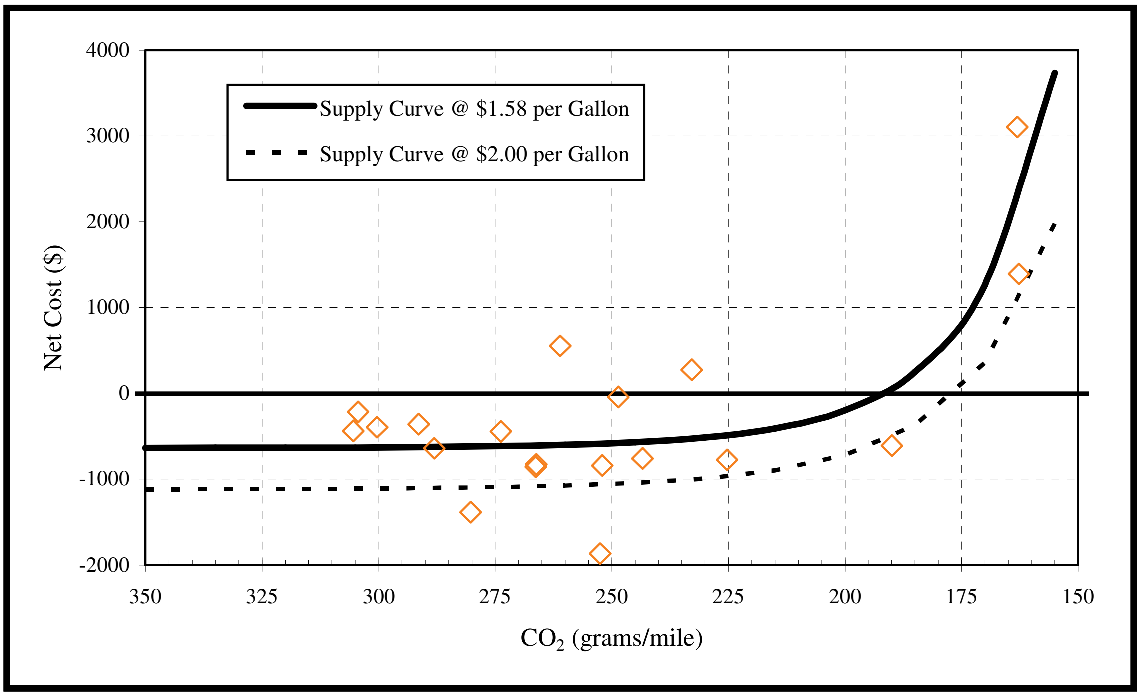
The solid line in Figure ES-2 represents the CO_2-reduction supply curve for the large car class. As indicated, CO_2 reductions of about 45 percent (corresponding to an emissions rate of 190 g/mi, relative to a 2002 vehicle at about 355 g/mi) are likely to be obtainable for a net negative cost (i.e. lifetime fuel savings exceed incremental technology costs). The figure also includes a second supply curve to show the results of a gasoline price sensitivity analysis in which the assumed prices of gasoline and diesel fuel are increased from $1.58 per gallon to $2.00 per gallon. At the higher fuel price (the dashed line in Figure ES-2), all but three of the technology packages reflect negative net costs, and the costs for two of those three are very nearly at the break-even point. A 42-volt cylinder deactivation package exhibits a net lifetime cost of $55, while the advanced gasoline hybrid-electric vehicle exhibits a net lifetime cost of $329. The advanced diesel hybrid still carries a net lifetime cost of about $2000.

At a gasoline price of $2.00 per gallon, estimated lifetime cost savings range from $400-$1100 for a vehicle achieving a CO_2 emissions rate of approximately 190 g/mi (this represents about a 45 percent reduction from the 355 g/mi emission rate of the corresponding baseline 2002 vehicle). Assuming a lower gasoline price of $1.58, lifetime cost savings are estimated to range from $0 (i.e., no net cost) to $600 for the same level of emission reduction. While diesel vehicles provide significant CO_2 reductions, the higher density of diesel fuel reduces the potential benefit of a given technology package relative to gasoline vehicles, especially as more aggressive carbon reduction scenarios are considered. For example, the two diamonds furthest to the right

[3] For purposes of this study, a supply curve indicates the relationship between CO_2 emissions reduction potential and cost.

in Figure ES-2 represent the gasoline (lower cost diamond) and diesel (higher cost diamond) advanced hybrid cases. While the two cases provide very similar CO_2 reductions, net costs for the diesel hybrid are about three times those of the gasoline hybrid (marginal vehicle costs are about 35 percent higher for the diesel vehicle). For less aggressive CO_2 reductions, diesel technology can be cost-effective as the fuel savings associated with increased diesel engine efficiency are large enough to offset the additional cost. However, it should be recognized that much of the gasoline engine technology evaluated here is specifically designed to close the gap between gasoline and diesel engine efficiency.

Figure ES-2: Net Vehicle Costs for the Large Car Class Given Two Gasoline Price Scenarios



ES-3.2. Small Car Results

Estimated emissions reductions for the 14 technology packages modeled for the small car class range from 11-56 percent, relative to the corresponding 2002 baseline vehicle. Some of the most cost effective packages include automated manual transmissions, turbocharging, and stoichiometric gasoline direct injection. Because this class of vehicles uses smaller engines, the use of 12-volt idle off technology was explored as an option. The results suggest that this technology is likely to be very cost-effective for the small car class. Unlike the other vehicle classes, cylinder deactivation was not evaluated for the small car class due to the small size of the baseline engine. Compared to the large car class, the costs for achieving equivalent CO_2 reductions are somewhat higher for certain technologies. There are two reasons for this result. First, technologies such as turbocharging that allow for engine downsizing provide substantial cost advantages in the other vehicle classes because they reduce cylinder count. However, at four cylinders, the base engine in the small car class is at the minimum cylinder count considered to have broad market acceptability from a performance and engineering standpoint. Thus, engine downsizing in the small car class does not generate the same level of cost savings estimated for engine downsizing in the other vehicle classes. Second, because the small car class has the lowest baseline CO_2 emissions and the lowest power-to-weight ratio of all the five classes, additional reductions accrue from a more aggressive baseline and carry somewhat higher costs.

The results for the small car class indicate that emission reductions of about 29 percent (from a baseline CO_2 emissions rate of 300 g/mi to about 215 g/mi) are likely to be obtainable at net negative cost (i.e. with net lifetime savings). The technology supply curve developed for the small car class suggests that all evaluated technology packages except the advanced hybrid and 42-volt advanced multi-mode diesel technology packages produce negative net costs at an assumed fuel price of $2.00 per gallon. Specifically, estimated lifetime cost savings at this higher fuel price range from $300-$500 for technology packages that achieve a CO_2 emissions rate of approximately 210 g/mi (equivalent to a 30 percent reduction from the 300 g/mi 2002 baseline). At a lower gasoline price of $1.58, estimated lifetime cost savings range from $0 (i.e., no net cost) to $250 for the same level of emission reduction.

ES-3.3. Minivan Results

Estimated emissions reductions (relative to the 2002 baseline vehicle) range from 14-54 percent for the 14 minivan technology packages studied. According to this analysis, combinations of technologies already used in some production gasoline models can reduce CO_2 emissions by approximately 25 percent. Examples of these technologies include 5 and 6-speed automatic transmissions, variable valve lift and timing, and cylinder deactivation. Reductions beyond this level will require the introduction of more advanced technologies such as gasoline direct injection, 42-volt starter generators, and camless valve technology. Even greater CO_2 reductions can be achieved using hybrid-electric designs. As with the large and small car cases, these advanced technologies are somewhat more costly than conventional gasoline technologies but fuel cost savings over the life of the vehicle usually far outweigh the additional cost. On a dollar per ton basis, the net cost of technologies required to produce CO_2 reductions up to 47 percent is negative, implying net lifetime cost savings.

Some of the most cost-effective packages evaluated for the minivan class include automated manual transmissions, cylinder deactivation, stoichiometric gasoline direct injection, turbocharging, and camless valve actuation.

As before, the technology packages evaluated in this class span a broad range of CO_2-reduction potentials and costs. For example, packages that achieve CO_2 reductions of 14-30 percent (i.e. emissions rates between 350 and 285 g/mi) encompass a net cost range from approximately negative $1,600 to negative $3. Emission reductions exceeding 29 percent (corresponding to a CO_2 emissions rate of 285 g/mi, relative to a 2002 baseline of 410 g/mi) are likely to be obtainable at net negative cost (i.e., achieving lifetime savings). At a higher fuel price of $2.00 per gallon, all evaluated technology packages reflect negative net costs except for the advanced gasoline and diesel hybrids. At this fuel price, estimated lifetime cost savings range from $800-$1,500 for technologies that reduce CO_2 emissions to approximately 220 g/mi (a 47 percent reduction from baseline 2002 emissions of approximately 410 g/mi). Assuming a lower gasoline price of $1.58, estimated lifetime cost savings range from $0-1,000 for the same level of emission reduction.

ES-3.4. Small Truck Results

Estimated emission reductions (relative to the 2002 baseline vehicle) range from 17-53 percent for the 14 small truck technology packages evaluated. According to this analysis, combinations of technologies already used in some production gasoline models can reduce CO_2 emissions by approximately 28 percent. Examples of these technologies include 6-speed automatic transmissions, variable valve lift and timing, and cylinder deactivation. Reductions beyond this level will require the introduction of more advanced technologies such as gasoline direct injection, 42-volt starter generators, camless valve actuation, and diesel engine technology. Some of the most cost-effective packages include stoichiometric gasoline direct injection, automated manual transmissions, turbocharging, camless valve actuation, and diesel technology. For example, a technology package consisting of stoichiometric gasoline direct injection and camless vale actuation can provide a 32 percent CO_2 reduction for an incremental vehicle cost of about $1,500. Even greater CO_2 reductions can be achieved using hybrid-electric technology. On a dollar per ton basis and taking into account lifetime fuel savings, the net cost of technologies producing CO_2 reductions up to 46 percent is negative, implying net cost savings over the vehicle life.

Packages that produce CO_2 reductions ranging from 17-32 percent (corresponding to CO_2 emission rates between 380 g/mi and 310 g/mi) encompass a net cost range from approximately negative $2,600 to negative $400. In fact, CO_2 reductions exceeding 45 percent are likely to be obtainable for a net negative cost. At a higher fuel price of $2.00 per gallon, all evaluated technology packages achieve negative net costs with the exception of the advanced diesel hybrid. At this fuel price, average lifetime cost savings range from $1,600 to $2,200 for CO_2 reductions to approximately 250 g/mi (equivalent to a 46 percent reduction from the 2002 baseline emissions rate of about 460 g/mi). Significant cost savings can actually be expected for technology packages that reduce CO_2 emissions rates to as little as 215 g/mi, nearly 54 percent below baseline 2002 emissions. At a lower fuel price of $1.58 per gallon, estimated cost savings are $700-$1,700 over the life of a vehicle, except in the advanced hybrid cases. In sum, the introduction of CO_2-reducing technologies in the small truck category provides high net savings due to the relatively high baseline CO_2 emissions for this class. This results in proportionately greater fuel savings compared to vehicle classes that start from a lower baseline CO_2 emissions rate.

ES-3.5. Large Truck Results

Emission reduction estimates range from 14-55 percent (relative to the 2002 baseline vehicle) for the 15 large truck technology packages modeled. According to this analysis, combinations of technologies already used in some production gasoline models can reduce CO_2 emissions by approximately 24 percent. Examples of these technologies include 6-speed automatic transmissions, variable valve lift and timing, and cylinder deactivation. Reductions beyond this level will require the introduction of more advanced technologies such as gasoline direct injection, camless valve actuation, and diesel technology, which can provide up to a 30 percent CO_2 reduction. Even greater CO_2 reductions can be achieved using hybrid-electric designs. On a dollar per ton basis, the net cost of technologies producing CO_2 reductions of up to 46 percent is negative, resulting in overall savings over the life of the vehicle.

Some of the most cost-effective packages in this class include automated manual transmissions, cylinder deactivation, and stoichiometric gasoline direct injection. Cylinder deactivation was evaluated as a more viable technology for large trucks than turbocharging and downsizing because of the need to assure adequate durability for heavily loaded engines operating on work-type duty cycles (e.g., high-load operations and payload and trailer towing).

The large truck category is the only vehicle class with an eight-cylinder base engine. Because of this, technology costs in the large truck class are in some cases higher than in the other vehicle classes due to additional hardware requirements. For example, eight lost motion devices are required for variable valve lift technology rather than six for other vehicle classes due to the additional cylinders. Despite these higher costs, fuel savings more than overcome incremental technology costs for nearly all the large truck technology packages evaluated.

Packages providing CO_2 reductions from 14 to 30 percent (corresponding to CO_2 emissions rates between 450 and 370 g/mi) encompass a net cost range from approximately negative $1,800 to positive $300. Emissions reductions of about 45 percent (corresponding to a CO_2 emissions rate of about 285 g/mi compared to a 2002 baseline rate of about 525 g/mi) are likely to be obtainable for a net negative cost (i.e., with net lifetime savings). At $2.00 per gallon of gasoline, all evaluated technology packages reflect negative net costs except the advanced gasoline and diesel hybrid cases. At this price, net lifetime fuel savings range from $900 to $1,700 for CO_2 reductions up to about 45 percent. At a lower gasoline price of $1.58, average lifetime savings range from $0 to $1,000 for this same level of CO_2 reductions.

ES-4. Conclusions

The results of this analysis suggest that existing and emerging automotive technologies can achieve substantial and cost-effective reductions in motor vehicle GHG emissions in the 2009 to 2015 timeframe. Specifically, GHG emissions from light-duty vehicles can be reduced from 14-55 percent in this timeframe. Assuming a gasoline price of $1.58 per gallon, this study found that most technology packages capable of achieving these reductions would result in net cost savings of at least $500, taking into account both incremental technology costs and fuel savings over the life of the vehicle. At a higher fuel price of $2.00 per gallon, estimated lifetime net savings are between $300 and $2,200 per vehicle for a range of CO_2 reductions - with the exception of some of the hybrid vehicles evaluated.

1. Introduction

1.1. Purpose of Study

This study provides an assessment of available and emerging technologies that could be used to reduce greenhouse gas (GHG) emissions from light-duty motor vehicles in the United States in the 2009-2015 timeframe. Its findings are drawn from the results of original cost and technology analyses conducted for this study, together with information obtained from other available reports. This assessment was inspired by the California legislature's passage of Assembly Bill 1493 requiring the state Air Resources Board (ARB) to adopt regulations designed to achieve the maximum feasible and cost-effective reductions in GHG emissions from light-duty vehicles beginning in model year 2009. The specific GHGs included in this assessment are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and hydroflourocarbons (HFCs).

The goal of this assessment is to help define GHG-reducing motor vehicle technologies that are expected to be feasible, commercially available and cost-effective in the 2009-2015 timeframe. A wide range of "off-the-shelf" and emerging technologies were evaluated, both individually and in packages, for their potential to reduce CO_2 emissions from light-duty vehicles. The technologies examined fall into six primary categories: (1) off-the-shelf engine technology; (2) off-the-shelf transmission technology; (3) emerging engine technology; (4) emerging transmission technology; (5) other vehicle technologies such as improved aerodynamics; and (6) other emerging technologies such as improved catalysts and HFC-free air conditioning. The study also includes an assessment of the potential penetration of these technologies into the fleet by the projection years of 2009 and 2015.

The results presented in this report have significant implications for states in the Northeast and elsewhere that share California's commitment to reducing transportation-related GHG emissions as part of a broader effort to address the risks posed by global climate change. In the Northeast, light-duty vehicles account for 20-25 percent of total emissions of manmade GHGs.

1.2. Basic Science of Global Climate Change

The climatic conditions to which humans and other species have become accustomed over thousands of years result from a complicated balance between the amount of solar energy that enters and leaves the atmosphere. In recent decades, a concern has emerged that human activities are interfering with this balance. Scientists have postulated that rising concentrations of certain heat-trapping gases in the atmosphere are enhancing a naturally occurring greenhouse effect which prevents some of the solar energy re-radiated from the earth's surface from leaving the atmosphere,[4] producing potentially significant shifts in global climate patterns.

[4] Without the naturally occurring greenhouse effect, the Earth's average temperature would be about 16°C (60°F) cooler, and climate conditions on the planet would be much closer to those that prevail on Mars. The consensus among the scientific community is that human activities are inadvertently enhancing this effect, with uncertain consequences for global climate conditions.

As noted at the outset, this assessment includes the primary GHGs that are commonly associated with current concerns about human-induced climate change (i.e. CO_2, CH_4, N_2O, and HFCs).[5] The heat-trapping properties of each of these gases – and hence their contribution to overall atmospheric warming – varies. Accordingly, scientists have developed the concept of "global warming potential" (GWP) under which each gas is assigned an index number that indicates its relative climate impact, over a specified period of time, expressed as an equivalent release (by weight) of carbon dioxide. For example, the current 100-year GWP assigned to methane is 21, which means that one ton of methane emissions is estimated to have the same global warming impact over 100 years as 21 tons of carbon dioxide emissions. The 100-year GWP values currently used in national and international GHG reporting for those GHGs included in this study are:

- carbon dioxide (CO_2) – 1
- methane (CH_4) – 23
- nitrous oxide (N_2O) – 296
- hydrofluorocarbons (HFCs) – various (up to 11,700)[6]

From the standpoint of anthropogenic emissions generally – and motor vehicle emissions specifically – the greenhouse gas of greatest concern is CO_2. Carbon dioxide is a natural by-product of the oxidation of carbon in organic matter, through either the combustion of carbon-based fuels or the decay of biomass; its chief sources globally are fossil fuel combustion and deforestation. This gas alone presently accounts for over 80 percent of total U.S. anthropogenic GHG emissions. The other gases listed above account for a much smaller portion of the overall U.S. GHG inventory[7] and also play a smaller role in terms of vehicle emissions.

Atmospheric measurements and analysis of air trapped in polar ice cores reveal that atmospheric concentrations of a number of GHGs are increasing. For instance, measured concentrations of carbon dioxide in the atmosphere have increased from pre-industrial levels of 278 parts per million (ppm) to 365 ppm in 1998. Methane has increased from 0.7 ppm to 1.745 ppm over the same period. Experts widely agree that human activities are responsible for these increases – most notably, fossil fuel combustion and tropical deforestation in the case of CO_2, and rice cultivation, animal husbandry, coal mining, natural gas handling, and waste disposal in landfills in the case of methane.[8]

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[5] Other naturally occurring and manmade gases (e.g., water vapor and perfluorocarbons) in the atmosphere also contribute to the greenhouse effect. Note that in general, all of the chief GHGs – with the exception of water vapor – are present in the atmosphere in only trace amounts. Nevertheless, they can have profound impacts on the earth's climatic balance. The most important GHG overall is water vapor. However, water vapor is not generated directly by human activities in quantities that are meaningful relative to natural sources.

[6] For motor vehicles HFC-134a constitutes the current HFC of concern and its GWP is 1,300.

[7] For example, the next most important manmade GHG after CO_2 is methane, which accounted for approximately 9 percent of the total U.S. inventory in 2000; for the same year the contribution from N_2O was 6 percent and all other gases were under 2 percent.

[8] National Research Council, Committee on the Science of Climate Change, *Climate Change Science: An Analysis of Some Key Questions* (Washington, DC: National Academy Press, 2001), p. 2.

Scientists have attempted to gauge the impacts of these changes on the global climate system with sophisticated computer models. The most recent assessment by the Intergovernmental Panel on Climate Change (IPCC), an international team of meteorologists and climate scientists convened under the auspices of the United Nations, found that global average surface temperature had increased by about 0.6 C (1 F) during the 20th century, and concluded that "In the light of new evidence and taking into account the remaining uncertainties, most of the observed warming over the last 50 years is likely to have been due to the increase in greenhouse gas concentrations." The most recent projections published by the IPCC project an increase in global average surface temperatures ranging from 5.8 C (2.5-10.4 F) over the next century, with warming for the United States as much as 30 percent higher than the global average.[9]

1.3. Environmental Impacts of Climate Change

Though climate change predictions remain fraught with uncertainties, even small changes in mean global temperature could have significant impacts. For example, average global temperatures during the last major ice age about 11,000 years ago were only about 3^{o}C (5.4^{o}F) lower than at present. Over subsequent millennia, average global temperatures have varied no more than 1.5^{o}C (2.7^{o}F). Moreover, the *rate* of climate change, as much as its eventual magnitude, may be critical to the successful adaptation of human and natural systems. A 2002 report by a special committee of the National Academy of Sciences warned that the impacts of climate change might not be gradual and linear: rather, increasing atmospheric GHG concentrations could push the climate system across thresholds that would trigger abrupt climate changes, such as alterations in major ocean currents or sudden regional increases in floods, droughts and other extreme weather events.[10]

In terms of the specific risks of climate change for the Northeast states, projections developed using the Canadian General Circulation Model and the United Kingdom's Hadley Climate Model suggest that average temperatures in New England could increase by 3.1-5.3^{o}C (about 6-10^{o}F) by the year 2090. A study funded by the U.S. Global Change Research Program noted that projected warming at the lower end of this range would raise average year-round temperature in Boston to a level currently measured in Richmond, Virginia, while – under the higher estimates – Boston's climate would be comparable to that of Atlanta, Georgia.[11] Associated impacts on the region could include more frequent and intense storms; increased damage in coastal areas from flooding and erosion associated with sea-level rise; higher numbers of heat-related deaths during summer heat waves; and a variety of stresses on forests, fishing grounds and coastal ecosystems which could in turn affect important economic sectors such as tourism, maple sugaring and skiing.

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[9] Intergovernmental Panel on Climate Change, Working Group I, *Climate Change 2001: The Scientific Basis*, Summary for Policymakers, pp. 2, 10, 13 (quote on p. 10).
[10] Committee on Abrupt Climate Change, National Research Council, *Abrupt Climate Change: Inevitable Surprises* (Washington, DC: National Academy Press, 2002).
[11] New England Regional Assessment Group, *Preparing for a Changing Climate: The Potential Consequences of Climate Variability and Change, New England Regional Overview* (University of New Hampshire: U.S. Global Change Research Program, 2001), pp. 6-7.

1.4. Political and Regulatory Context

1.4.1. International Context

As early as 1992, international awareness of the many potential risks associated with global warming led 160 countries, including the United States, to adopt a Framework Convention on Climate Change under the stated objective of achieving "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system."[12]

Toward this objective, signatories pledged to work to stabilize greenhouse gas emissions. A number of industrialized countries, again including the United States, adopted the specific near-term goal of returning year 2000 greenhouse gas emissions to 1990 levels. It subsequently became evident that most countries, including the United States, were not on track to meet this objective. In response, parties to the Framework Convention adopted the Kyoto Protocol in 1997, which included targets and timetables for reducing GHG emissions to specific levels for each country. As of early 2003, 102 countries had ratified or acceded to the Protocol. However, the United States – citing concerns about the economic impact of reducing GHG emissions on the time scale required under the agreement – has not ratified the Kyoto Protocol.

Notwithstanding the federal government's reluctance to impose mandatory limits on GHG emissions, many state and local leaders had become sufficiently concerned about the issue of climate change by the end of the 1990s to adopt a range of measures aimed at reducing GHG emissions within their jurisdictions. This trend began with a few leading states in the early 1990s, but has accelerated recently: in 2001 and 2002, approximately one-third of the states passed new legislation or executive orders specifically aimed at reducing greenhouse gas emissions.[13] These policies ranged from comprehensive state action plans with quantitative GHG reduction targets to regulations or laws limiting emissions from a specific sector such as electric power generation or transportation.

1.4.2. California's Assembly Bill 1493

In 2003, the California legislature passed legislation (Assembly Bill 1493) aimed at reducing GHG emissions from motor vehicles in response to concerns about the potential impact of global climate change on the state's economy and on the well-being of its citizens. The bill, which was signed into law by Governor Davis on July 22, 2002, requires the state's Air Resources Board to adopt regulations by 2005 that will achieve the maximum feasible reductions in GHG emissions from new light-duty vehicles that can be achieved in a cost-effective manner beginning with the 2009 model year. In achieving that goal the state is specifically prohibited, under the legislation, from

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[12] United Nations, "Report of the Intergovernmental Negotiating Committee for a Framework Convention on Climate Change on the Work of the Second Part of Its Fifth Session, Held at New York From 30 April to 9 May, 1992," UN Document A/AC.237/18, Part II (May 15, 1992).

[13] Additionally, other states adopted measures that were not expressly aimed at climate change but clearly were driven at least in part by the issue of global warming. Barry G. Rabe, *Statehouse and Greenhouse: The Evolving State Government Role in Climate Change* (Arlington, VA: Pew Center on Global Climate Change, November 2002), p. 7.

adopting any regulatory requirements that would mandate vehicle weight reductions, restrict sales of any particular vehicle type, or impose fees or taxes on vehicles or vehicle miles traveled. AB 1493 also provides for a legislative review process.

The standard adopted by ARB is required to account for CO_2, CH_4, N_20 and refrigerant (HFC) emissions. Particulate matter (PM) emissions may not be included due to the limited availability of data and the fact that PM emissions are regulated under California's low emission vehicle (LEV II) program. In addition, the form of the standard developed to implement AB 1493 must be carefully designed to provide for effective and equitable GHG reductions. Options that ARB staff have considered for the form of the standard include manufacturer-specific standards, a uniform fleet average standard, an attribute-based approach, a weight-based approach and a weight category approach.

1.4.3. Climate Actions in the Northeast States

In 2002, the Conference of New England Governors and Eastern Canadian Premiers (NEG/ECP) adopted a regional climate action plan covering the New England states and the five eastern Canadian provinces of Quebec, New Brunswick, Nova Scotia, Newfoundland, and Prince Edward Island. The NEG/ECP climate plan sets overall regional targets for stabilizing aggregate GHG emissions at 1990 levels by 2010, followed by a ten percent reduction below 1990 emissions levels in 2020 and substantial further reductions (by as much as 75 to 80 percent) in subsequent years. In recent years, other northeastern states – notably New York and New Jersey – have developed or undertaken their own GHG reduction initiatives, and in some cases have set their own reduction targets. Given that the transportation sector accounts for a significant portion of the overall increase in emissions projected for the region in future years, achieving the region's climate goals will require effective means to address the motor vehicle contribution. In that context, Northeast states are closely monitoring the AB1493 rulemaking and some have already expressed an interest in adopting any new California requirements that are likely to result.

In 2003, for example, a proposal to adopt California's regulations for the control of GHG emissions from motor vehicles was included in New York Governor George Pataki's State of the State address and was formally introduced in the New York state legislature.[14] Additionally, the idea was included in policy recommendations submitted by the New York State Greenhouse Gas Task Force which was created by Governor Pataki to develop proposals for reducing the state's GHG emissions. In fact, the Northeast states have an established track record of adopting California's more stringent motor vehicle regulations: several of them have been enforcing California's Low Emission Vehicle (LEV) standards in lieu of federal emissions standards for over a decade.

[14] Specifically, New York Senate bill S. 4044 (Assembly bill A. 4082) would require the New York State Department of Environmental Conservation to promulgate California's regulations for the cost effective control of GHG emissions from motor vehicles by December 31, 2005 (i.e., one year from the January 1, 2005 deadline for promulgation of California's rules).

1.5. Report Organization

This report is divided into three sections: Chapter 1, *Introduction*, describes the purpose of the report, provides a short summary of the state of the science of climate change and describes the current political and regulatory context for this assessment. Chapter 2, *Overview of Study Method*, describes the computer simulation models used in this assessment, discusses the selection of potential GHG reduction technologies, describes the approach used to define vehicles for the baseline assessment, explains the approach used to assess and package technology options, and describes the methodology used to project deployment costs for individual technologies and packaged combinations. Chapter 3, *Results*, presents the findings of the technical and cost analyses performed for this study. It also compares the findings of other recent studies with regard to costs. This report contains results for five classes of vehicles. Technical appendices provide detailed results of the model simulations, supporting analyses, and cost analyses.

2. Overview of Study Method

This chapter provides an overview of the methodology used to estimate GHG reductions that could be achieved by introducing advanced technologies into the U.S. light-duty[15] vehicle fleet in the 2009-2015 timeframe. The core of the analysis consists of a series of modeled simulations to predict the emissions impacts of incorporating various technology combinations in new vehicles. A more detailed description of the specific methods and assumptions used in the analysis is provided in Appendix B.

All simulation modeling for this study was performed using AVL Powertrain Engineering, Inc.'s CRUISE software, which provides detailed information on the acceleration, braking, and emissions performance of different motor vehicle designs, including advanced powertrain designs. The modular structure of CRUISE can accommodate a variety of vehicle configurations – including cars, motorcycles, trucks, and buses – and allows for the detailed specification of a wide range of individual vehicle components. This enables the user to investigate – at the vehicle level of detail – how modifying or replacing certain components, either individually or in combination, affects vehicle performance across a number of parameters, including over standardized city and highway driving cycles; in terms of climbing performance; steady-state and top speed performance; maximum acceleration and traction force; and braking performance.[16] A more detailed description of the CRUISE software is included in Appendix B.

Remaining sections of this chapter describe each basic step of the analysis methodology, In brief, these steps consisted of:

1. Defining five representative vehicle classes (i.e., small car, large car, small truck, large truck, and minivan).
2. Validating model simulation results against the actual performance of representative 2002 model year vehicles in each class and developing a "business-as-usual" technology baseline for each class of vehicles in model year 2009.
3. Developing a list of specific technology options and assessing the costs and potential GHG-reducing benefits of each option in isolation.
4. Constructing various technology combinations or "packages" based on the results of the above assessment of individual technology options.
5. Performing CRUISE model simulations for each of the vehicle classes and technology packages selected for analysis.
6. Assessing the emissions reduction benefits of additional technology options such as low rolling resistance tires, low viscosity lubricating oil, vehicle mass reduction, air conditioning options, and hybrid vehicle technologies.
7. Assessing the costs and benefits of different technology packages.

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[15] Consistent with the classifications used in most existing state and federal regulations, light-duty vehicles are defined in this study as vehicles with a Gross Vehicle Weight Rating (GVWR) less than 8,500 lbs.

[16] The range of components that can be individually specified in CRUISE includes: vehicle and trailer; engine (combustion or electric motor); clutches; transmission elements; control elements; shafts (rigid or torsion-elastic); wheel/tire; electrical components; hybrid components; brakes; and auxiliaries (such as oil pump, air conditioning or power steering). In addition, the software allows for modification of assumptions about the driver and about environmental driving conditions (such as wind, road surface, etc.).

2.1. Defining Representative Vehicle Classes

For purposes of this study, vehicles were first categorized according to major utility distinctions using 2002 sales and technology data. The objective was to determine the minimum number of classes that would provide for maximum fleet representation while maintaining reasonably homogeneous technology composition within classes. A total of five vehicle classes were selected: large cars, small cars, large trucks, small trucks, and minivans. The small car class generally includes vehicles defined by the U.S. Environmental Protection Agency (EPA) as subcompacts and compact cars, while the large car class includes EPA midsize and large cars. The small and large truck classes include both pickup trucks and sport utility vehicles (SUVs) and are generally split according to gross vehicle weight rating (at approximately 6000 pounds). In most cases, SUVs and pickup trucks share a common platform and utilize similar engine and driveline technology, so representing them in combination is consistent with current technology distinctions. Table 2-1 summarizes the chief characteristics of each vehicle class evaluated in this study and indicates its prevalence in recent (2002) overall light-duty vehicle sales.

Table 2-1: Characteristics of Evaluated Vehicle Class

Vehicle Class	Fraction of Sales in 2002	Dominant Technology Characteristics
Small cars	22%	4-cylinder, naturally aspirated, dual overhead cam (DOHC), four-speed automatic transmission, front wheel drive vehicles
Large cars	25%	6-cylinder, naturally aspirated, DOHC, four-speed automatic transmission, front wheel drive vehicles
Small trucks	23%	6-cylinder, naturally aspirated, DOHC, four-speed automatic transmission vehicles, with a nearly 50/50 split between two and four wheel drive
Large trucks	21%	8-cylinder, naturally aspirated, overhead valve (OHV), four-speed automatic transmission vehicles, also with a nearly 50/50 split between two and four wheel drive
Minivans	7%	6-cylinder, naturally aspirated, OHV, four-speed automatic transmission, front wheel drive vehicles

For each of these vehicle classes, AVL modeled a production vehicle that best matched the average characteristics of vehicles in each class. Determining the average characteristics required specifying both numeric and non-numeric parameters. For vehicle characteristics that could be specified using continuous numeric parameters — such as curb weight, engine displacement, peak horsepower, peak torque, etc. — the value assumed for the model vehicle simply reflected the sales-weighted numeric average of actual model year 2002 vehicles in each class. For other non-numeric vehicle characteristics that could not simply be averaged,[17] the model vehicle was assumed to include whatever discrete technology accounted for the largest share of 2002 class sales.

[17] For example, a particular class of vehicles might be split evenly between 4-speed and 5-speed automatic transmission models. However, it is not possible to model a theoretical 4.5-speed "average" of these two characteristics.

For example, 31 percent of large cars sold in 2002 had overhead valves, whereas 24 percent had single overhead cam (SOHC) and 45 percent had dual overhead cam (DOHC) valvetrain technologies. Since DOHC technology has the largest sales share, it was taken as the class average valvetrain technology for the model large car. Table 2-2 summarizes the specific characteristics assumed for the representative, model vehicle in each of the five vehicle classes analyzed.

Table 2-2: 2002 Class Average Statistics

Parameter	Large Truck	Small Truck	Minivan	Large Car	Small Car
Curb Weight (lbs)	4826	3714	3980	3380	2762
GVWR (lbs)	7167	4867	NA	NA	NA
Displacement (liters)	5.01	3.41	3.42	3.18	2.27
Engine Type	V8	V6	V6	V6	L4
Charge Type	NA	NA	NA	NA	NA
Cam Type	OHV	DOHC	OHV	DOHC	DOHC
Rated HP	257	195	199	194	148
Peak Torque (lb-ft)	311	218	222	208	152
Driveline	4WD	4WD	FWD	FWD	FWD
Transmission Type	Automatic	Automatic	Automatic	Automatic	Automatic
Speeds	4	4	4	4	4
CO_2 (g/mile - combined)	574	473	436	385	334
HP/Weight Ratio	0.0537	0.0524	0.0498	0.0569	0.0530
Torque/Weight Ratio	0.0649	0.0586	0.0558	0.0610	0.0545

2.2. Validating Simulation Modeling Results for Representative Vehicles and Developing a "Business-As-Usual" Technology Baseline

As described in the foregoing section, the specifications used to describe a representative or "average" vehicle in each vehicle class for simulation purposes were based on actual 2002 vehicle characteristics. However, no one, actual vehicle has characteristics that exactly match the combination of average or representative specifications developed for each vehicle class. Hence, to validate model simulations of the average vehicle, it was necessary to identify actual vehicle platforms that were close to the calculated class averages in terms of technology and performance. To identify candidate vehicles, a series of parameter-by-parameter closeness statistics was developed for every actual model year 2002 vehicle in each class to indicate the degree of similarity with the class average characteristics summarized in Table 2-2[18] The smaller the

[18] In all, closeness statistics were developed for a total of 14 vehicle parameters. See Appendix C for further details.

closeness statistic, the closer the particular vehicle is to the theoretical class average vehicle — with a value of zero being indicative of an exact match. Based on a rank ordering of the overall closeness statistic for different vehicle platforms, the actual vehicle selected to validate simulation results for the model or average vehicle in each class was as follows:

- Small cars: Chevrolet Cavalier 2.2 liter L4
- Large cars: Ford Taurus 3.0 liter V6
- Small trucks: Toyota Tacoma 3.4 liter V6
- Large trucks: GMC Sierra 5.3 liter V8
- Minivans: Chrysler Town & Country 3.3 liter V6

To validate the simulation methodology, model-predicted performance in terms of CO_2 emissions and acceleration (0-60 time) was compared to actual data for each of these vehicles. The results, which are summarized in Table 2-3, generally suggest that the model simulations provide good estimates of actual vehicle performance. In terms of CO_2 emissions, for example, the simulated values are within one percent of the actual values for the representative vehicles and within two percent of the class average for all but the small truck class. Combining the performance of the simulation models for all five vehicle classes using the appropriate sales weighting (i.e., 0.211 for large trucks, 0.238 for small trucks, 0.067 for minivans, 0.262 for large cars and 0.222 for small cars), yields a fleetwide CO_2 emissions error of 2.0 percent. To the extent that the effect of this error is the same for both estimated baseline and controlled CO_2 emissions, it is unlikely to affect estimates of the relative difference between them.

Having validated model performance for each of the class-average 2002 vehicles, the next step was to develop a "business-as-usual" baseline for technologies likely to be incorporated in vehicles by model year 2009. Given that vehicle technology will certainly evolve over the coming years, even absent policy intervention to reduce GHG emissions, this step was necessary to provide a more realistic baseline against which future emissions reduction potential and incremental cost could be evaluated. For example, to the extent that some new technologies are likely to be adopted in response to existing market forces, they may not be available for additional CO_2 reductions in the projection years. Moreover, to the extent that many of these new technologies are likely to be applied in ways that improve vehicle performance rather than reduce emissions, some or all of their associated emissions reduction potential will also not be available. To estimate the potential impacts of new technology adoption and analyze potential tradeoffs between improved vehicle performance and emissions reductions, the 2002 models were adjusted to incorporate new technologies that are expected to enter the fleet between 2002 and 2009.

Table 2-3: Performance of the 2002 Simulation Models

Parameter	Large Truck	Small Truck	Minivan	Large Car	Small Car
CO_2 (grams/mile)					
Representative Vehicle	499	427	375	331	276
Model	493	426	376	329	278
Delta	-6.5	-1.4	+1.3	-1.3	+1.4
Delta (percent)	-1.3	-0.3	+0.3	-0.4	+0.5
Class Average	488	400	371	327	281
Delta	+4.8	+25.7	+5.8	+2.5	-3.5
Delta (percent)	+1.0	+6.4	+1.6	+0.8	-1.3
0-60 Time (seconds)					
Representative Vehicle	9.0	9.7		8.1	8.2
Model	8.9	10.0	10.5	8.1	8.7
Delta	-0.14	+0.29		-0.03	+0.54
Delta (percent)	-1.6%	+3.0%		-0.4%	+6.6%

To project a "business-as-usual" evolution in vehicle technology and attributes over the coming years, Martec conducted detailed market research into Original Equipment Manufacturer (OEM) product plans and developed a database of estimated 2009 vehicle platforms under baseline conditions. Baseline in this case means that only currently adopted regulatory requirements were assumed in developing the 2009 vehicles. The resulting database was used to adjust the 2002 class average vehicle characteristics that were simulated to reflect expected 2009 baseline technology and performance.

The biggest technology changes anticipated between 2002 and 2009 are:

- Near-universal use of cam phaser (variable valve timing) technology. However, the sophistication of this technology is likely to vary across models (i.e., intake valve only, exhaust valve only, both intake and exhaust valves in a coupled or dual independent configuration, etc.),
- Significant penetration of variable valve lift technology into the fleet,
- Significant penetration of cylinder deactivation technology into the fleet,
- Continued evolution of transmission technology, with six speed automatic transmissions becoming dominant, and
- Limited growth in the market share of stoichiometric gasoline direct injection (GDI) and diesel engines as well as turbocharger and hybrid-electric vehicle technologies.

Existing market forces that are comprehended in the development of the 2009 baseline fleet characteristics and technology penetration include:

- Light truck CAFE progression from 20.7 mpg to 22.2 mpg in MY2007;
- The California ZEV mandate, also adopted by New York and Massachusetts (at the time this study was completed);
- Full implementation of Federal Tier 2 emissions standards, which drives a broad requirement for improved cold-start performance;
- Increased competition in the North American market across all product segments, which drives OEMs to create differentiation on many vehicle attributes, including performance;
- Installed powertrain capital base; and
- OEM positioning, sale mix and anticipated attempts to balance market, regulatory and societal forces.

It is important to note that the 2009 baseline vehicles were not created as a least cost solution for CO_2 reductions. In fact, CO_2 reductions were not a consideration in the 2009 baseline vehicle forecast, except to the extent that they were influenced by responses to the market forces or regulatory requirements described above. The projections in technology penetrations for 2009 were developed solely in response to the market forces and trends listed above that will affect manufacturing and design decisions between now and 2009. For example, the projection of near universal use of cam phasers in 2009 is based on the need to reduce cold start emissions in order to meet Tier 2 standards. Similarly, the use of six speed automatic transmissions is based on the forecasted need to provide better acceleration and a smoother ride in order meet expected consumer demands.

As before, when dealing with discrete vehicle technologies that cannot be averaged for purposes of the vehicle simulation, it was necessary to predict which technology would dominate in 2009. Table 2-4 summarizes the predicted dominant characteristics of class average vehicles in 2009 in comparison to 2002 models. As indicated by the shaded cells, forecasted changes in dominant technologies are limited to transmission and valvetrain technologies.

Table 2-4: Dominant Discrete Technologies in 2002 and 2009

Parameter	Large Truck		Small Truck		Minivan		Large Car		Small Car	
	2002	2009	2002	2009	2002	2009	2002	2009	2002	2009
Engine Type	V8	V8	V6	V6	V6	V6	V6	V6	L4	L4
Charge Type	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Cam Type	OHV	OHV	DOHC	DOHC	OHV	OHV	DOHC	DOHC	DOHC	DOHC
Driveline	4WD	4WD	4WD	4WD	FWD	FWD	FWD	FWD	FWD	FWD
Transmission	A4	A6	A4	A6	A4	A5	A4	A6	A4	A5
Cam Phasing	No	Coupled	No	Dual	No	Coupled	No	Dual	No	Dual
Variable Lift	No	No	No	Discrete	No	Discrete	No	Discrete	No	Discrete
Cyl. Deact.	No	No	No	No	No	No	No	No	No	No

Under "business-as-usual" assumptions one would expect changes not only in vehicle technology, but in vehicle performance and other attributes over the next several years. To estimate the impacts of these changes, a trend analysis was conducted using data published by the EPA.[19] Specifically, historical trends in vehicle weight and 0-60 acceleration time for the period 1993-2003 were analyzed and used to project continued changes to 2009. Table 2-5 summarizes the results of the historical trend analysis for each of the five vehicle classes considered.

Table 2-5: Trend-Based Forecast Parameters

Parameter	Large Truck	Small Truck	Minivan	Large Car	Small Car
Inertia Weight (1993-2003)					
Change per Year (pounds)	42	25	32	0	22
0-60 Time (1993-2003)					
Change per Year (seconds)	-0.22	-0.15	-0.19	-0.14	-0.11

As indicated in Table 2-5, all vehicle classes exhibited significant increases in power (as measured by how quickly they can accelerate from 0-60 mph) and four of the five classes exhibited significant (and simultaneous) weight increases over the last 10 years (the exception was large cars, which did not get appreciably heavier over this time period). The trend in improved power (as measured by a decline in 0-60 time) was assumed to continue without change to 2009 in all classes. However, the trend toward increased weight was assumed to moderate, largely in response to the small increase in Corporate Average Fuel Economy (CAFE) requirements anticipated for light trucks over the next several years.[20] Accordingly, weight was held constant for the truck and minivan classes, as well as for large cars, leaving only the small car class with an expected average weight increase of 152 pounds between 2002 and 2009.[21]

Once baseline 2002 vehicle characteristics had been updated to 2009 using the Martec technology database, a validation check was performed to determine whether the 2009 model forecasts were sensitive to possible variations in the penetration of discrete technologies.[22] This check was performed by identifying the various discrete technology packages that commanded a five percent or greater share of the 2009 market in each vehicle class. Discrete CO_2 impact estimates developed by AVL were then used to estimate the overall CO_2 impact of each technology package and the results were

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[19] U.S. Environmental Protection Agency, *Light-Duty Automotive Technology and Fuel Economy Trends: 1975 Through 2003*, EPA420-R-03-006, Appendices G and H, April 2003.

[20] For light trucks, the CAFE standard will remain at 20.7 mpg for model years 2002-2004, and increase to 21.0 mpg in model year 2005, 21.6 mpg in model year 2006 and 22.2 mpg in 2007.

[21] The large car weight was held constant given the lack of weight increase between 1993 and 2003.

[22] For example, though the dominant technology characteristics for large trucks include cam phasing without variable lift, a 6-speed automatic transmission and no cylinder deactivation, the fraction of the large truck fleet actually represented by this combination of technologies is less than six percent. This is an artifact of the increasingly diverse set of technologies available to manufacturers, which results in a situation where technologies that are dominant when viewed in isolation are spread across an otherwise diverse fleet.

weighted by market penetration to estimate an overall class-specific CO_2 impact. Given that the results of this evaluation showed a maximum CO_2 emissions difference of 1.5 percent (6.8 grams per mile), the dominant class-average 2009 technology packages developed using this methodology are believed to accurately represent likely 2009 fleet CO_2 emissions.

2.3. Identifying Discrete Vehicle Technology Options for Evaluation

Table 2-6 lists the individual vehicle technologies considered in this study for purposes of evaluating future light-duty vehicle CO_2 emissions reduction potential. A brief description of each of the technologies indicated in Table 2-6, – including an explanation of how each option might reduce CO_2 emissions – is provided in Appendix A.

As a first step toward identifying individual technology options for further evaluation, the potential CO_2 emissions impact of each of the options listed in Table 2-6 was evaluated in isolation. The purpose of this evaluation was primarily to screen for the most promising technologies to be included in the more detailed "package" simulations conducted later in the analysis. Accordingly, this step was not intended to be precise and was implemented, to the extent feasible, using simplified approaches. In many cases, for example, an engine map was selected and the CO_2 emissions rate at a specific point on that map was compared to the corresponding point on the base technology engine map for each representative vehicle.[23] This comparison was made at the speed/load point that represented average simulated vehicle CO_2 emissions over the highway and city cycles. For technologies that provided the bulk of their benefits through a shift in speed/load performance (i.e., primarily transmission technologies), a full CRUISE simulation was run for the candidate technology and compared to that for the applicable representative vehicle. Where engine maps were not readily available, impact estimates were developed through a review of available research papers.

In addition to estimating the emissions reduction potential of each of the individual technology options listed in Table 2-6, rough cost estimates were developed for each option to gauge the relative cost-effectiveness of employing one GHG reduction technology versus another. This task was performed by Martec using available information on incremental vehicle system and component hardware costs. Incremental business costs to vehicle manufacturers or impacts on the retail price of vehicles from a consumer perspective were not evaluated at this stage of the analysis.[24]

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[23] An engine map is a graph that provides pollutant or fuel consumed at a corresponding rpm and torque value over the full operating range of the engine.

[24] In order to evaluate possible retail costs and to compare the Martec projections with costs published in other studies, NESCCAF developed an RPE for each of the Martec costs. The RPE is discussed in section 2.6 of this chapter.

Table 2-6: Vehicle Technologies Evaluated in this Study

Engine Technologies	***Drivetrain Technologies***
Cam Phasing	5-Speed Automatic Transmission
• Single cam phaser	6-Speed Automatic Transmission
• Dual cam phaser	Continuously Variable Transmission (CVT)
• Coupled cam phaser	Automated Manual Transmission (6 speed)
Variable Valve Lift	42 Volt ISG - Idle Off
• Discrete Valve Events	42 Volt ISG - Launch Assist, Regen, Idle Off
• Continuously Variable	Motor Assist Hybrid
Camless Valve Actuation	Fully Integrated Hybrid
• Electromagnetic Actuation	Aggressive Shift Logic
• Electrohydraulic Actuation	Early Torque Converter Lock-up
Turbocharging	***Other Load Reducing Technologies***
• Variable Geometry	Advanced Power Steering
• Electric Assist	• Electrohydraulic
Cylinder Deactivation	• Electric
Variable Compression Ratio	Electric Oil and Water Pumps
Variable Charge Motion	Improved Alternator
Gasoline Direct Injection - Stoichiometric	Engine Friction Reduction
Gasoline Direct Injection - Lean Burn Stratified Charge	Improved Lubricating Oil
Gasoline Homogeneous Charge Compression Ignition	Air conditioning technologies and refrigerants
Diesel High Speed Direct Injection	***Vehicle Technologies***
Diesel Advanced Multi-Mode Combustion	Aerodynamic Drag Reduction
	Mass Reduction
	Improved Tire Rolling Resistance

Overall, the study encompassed technologies that are either already in production for the U.S., European, or Japanese car markets or known to be planned for production in these markets; technologies identified by AVL or by other members of the NESCCAF GHG Study Team; and technologies defined in the automotive literature. Through discussions with AVL and other members of the study team, Martec assembled detailed functional definitions of each of the GHG reduction technologies as they were modeled by AVL. This detail was especially important in instances where a technology option covered a wide variety of functional definitions and mechanizations (e.g., valve train technologies). Specifically, Martec was provided with:

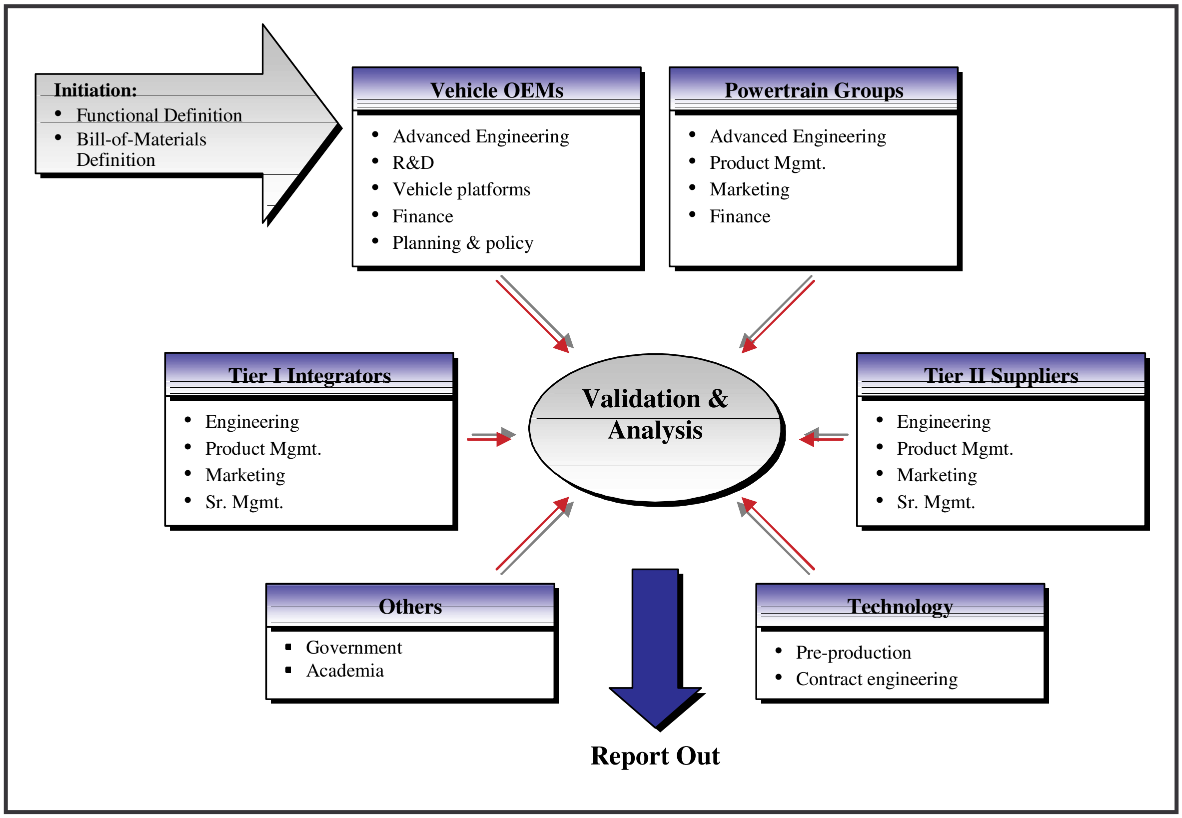
- A written functional description from which a bill of materials was developed;
- A reference automotive industry technical specification for the technology;
- A reference to an existing vehicle and architecture; or
- A reference to a particular supplier implementation of the technology.

In instances where such sources were not available, Martec gathered industry information on specific technologies using interviews and technical papers. Field interviews were conducted with individuals representing all aspects of the automotive industry, including the management, engineering, purchasing, finance, planning and product management divisions of both manufacturers and parts suppliers. Wherever possible, information gleaned from technical papers was verified in interviews. In general, Martec sought to obtain input from two or more automakers and two or more suppliers for each technology studied.

Figure 2-1 illustrates the methodology used by Martec to develop technology cost estimates for this study. Generally speaking, it was not necessary to investigate the design details of different technologies except in some cases where these details needed to be understood to reconcile differences in the cost estimates provided by various sources. Ultimately, all of the costs used in the analysis represent industry-accepted technology applications that also meet the functional requirements provided by AVL.

The results of Martec's cost analysis were reported in the form of a matrix which allows for easy calculation of the net, vehicle-level *difference* in hardware costs (relative to a baseline vehicle) for any given package of technologies applied to each of the five different vehicle types studied for this analysis. The cost matrix is summarized in Chapter 3 which presents the results of this study, and is detailed in Appendix C. Net hardware costs in this context include system and component costs, as well as applicable credits in instances where the use of a particular technology would reduce other component or system costs (for example, some technology packages evaluated eliminate the need for EGR). Credits were also included for downsizing engines when certain technologies, such as turbochargers, were applied. Finally, separate cost estimates were developed for some technology combinations that involved overlapping systems or costs – such as variable valve lift and cylinder deactivation systems.

Figure 2-1: Overview of the Martec Costing Methodology



As noted at the outset of this section, Martec's cost estimates do not attempt to capture all costs to the manufacturer of incorporating new technologies, nor do they include estimates of cost impact at the consumer level as reflected in the purchase price of a new vehicle. Additional manufacturer-level costs that were not captured in this analysis but that could be associated with the use of new technologies include:

- Engineering costs, including advanced R&D, vehicle design and development engineering for integrating new technologies and software development;
- Warranty and possible recall costs;
- Factory capital costs associated with vehicle-level technology changes;
- Manufacturing costs for powertrain or vehicle assembly.

The costs described by Martec represent an estimate of the cost to the manufacturer for the hardware needed to incorporate a given GHG-reducing technology on a high-volume production vehicle. Associated system-level material content such as wires, control module drivers, etc. are included in these estimates – if purchased from a supplier, these all represent a variable cost to the automaker. However, the estimates do not necessarily capture the complete set of variable costs that might be associated with the introduction of new technologies – for example, applying some technologies might require body and chassis re-designs that would in turn incur additional costs.

For purposes of estimating net hardware costs, all baseline vehicles are assumed to use gasoline stoichiometric control systems and exhaust aftertreatment systems. In addition, all are assumed to be average vehicles using EGR systems. The incremental cost of exhaust aftertreatment was included when assessing net cost differences for engine-type technologies. All study vehicles (baseline and future technology packages) were required to meet the U.S. Tier 2, Bin 5 emissions standards using systems forecast for usage in the 2009 model year. A consistent scalable model for stoichiometric aftertreatment systems was applied by Martec for all vehicles. Lean burn (gas and diesel) aftertreatment systems, based upon designs provided by AVL and NESCCAF from other industry sources, were also costed by Martec.

All costs are presented in 2003 U.S. dollars and assume that the subject technologies will be manufactured in a highly competitive environment using flexible and lean manufacturing methods.[25] Costs are estimated for the year 2009 and beyond assuming that each manufacturer (automaker or supplier) will produce at least 500,000 units per year, thereby achieving full economies of scale. A flexible and lean manufacturing environment presumes fast execution of the cost and quality learning curves for the product design and manufacturing process. It is therefore a key assumption underlying the cost estimates and was clearly specified in all industry interviews and analyses concerning the likely costs of different technology advances. More specifically, Martec assumed that at least three high-volume automakers would use each technology at volumes of at least 500,000 units per year and that at least three competing suppliers were available to supply each automaker for each technology. This would create a highly competitive purchasing environment that would drive prices and costs to competitive levels. In addition, Martec assumed that the cost of each technology to the vehicle manufacturer would be the same whether it was provide by an outside supplier or made by the manufacturer. Generally speaking, the resulting cost estimates for each technology represent the least costly product option that meets the technology functional requirements and is recognized as viable in the industry. Importantly, Martec did not assume future cost reductions due to currently unknown advances in either technology design or manufacturing - future costs reflect fully learned, high-volume production of current technology designs. To the extent that basic scientific advances in design or manufacturing do occur, future costs may be lower than estimated.

2.4. Assembling Technology Packages for Model Simulation

Using the most promising individual technologies that emerged from the initial screening evaluation described above, in combination with cost estimates for the individual technologies, a series of technology packages was assembled for each vehicle class. Generally, these packages were designed to span the full range of CO_2 reduction potential (i.e., from modest to substantial reductions), so they necessarily reflect a range of impacts (and costs). The specific packages evaluated, along with the model simulation results for each package are presented in the next chapter (Chapter 3).

A full CRUISE simulation was then performed for each technology package, using the performance constraints identified for 2009 models. In cases where the

[25] Lean manufacturing methods involve creating manufacturing modules of modest volumes and duplicating those modules for additional volume.

technology package being analyzed produced performance benefits over and above the forecast baseline, the vehicle engine was downsized or the vehicle axle ratio was adjusted so that estimated emissions benefits reflect constant vehicle performance. As indicated earlier in this chapter, the CRUISE software is designed to simulate CO_2 emissions and vehicle performance for different combinations of engine and driveline technologies. For this project, vehicle performance includes full-load acceleration from rest to 60 mph, from 50 mph to 70 mph in top gear (representing a passing situation), full-load climbing performance at curb and gross vehicle weights, and the maximum velocity of the vehicle. Additional detail about the CRUISE simulations is provided in Appendix B.

An important benefit of simulating the performance of technology packages, rather than individual technologies, is that it eliminates the possibility that CO_2 reductions will be "double counted." The emissions benefits associated with various options are not necessarily additive when these improvements are combined in a single vehicle, particularly to the extent that many technologies target the same sources of mechanical or thermodynamic inefficiency. The simulation modeling conducted for this analysis avoids this problem. At the core of each simulation is an engine map that defines CO_2 emissions over a full range of engine speed and load points. Each map reflects the contribution of all engine technologies incorporated in the vehicle and therefore accounts for their composite impact on CO_2 emissions. Engine maps were completely replaced for each technology package simulated in this analysis; they were not added or otherwise manipulated. In the case of technologies that do not directly affect the engine map but rather the point on the map at which a vehicle is operating (e.g., transmission technologies), the simulation model ascribes benefits to those technologies (in combination with all other included technologies) in accordance with their cumulative effect on engine operation. Thus, at any given point in time, the vehicle is simulated as operating at one speed/load point as determined by the *combination* of technologies present; in turn, the specific CO_2 emissions rate for that point in time is simply read from the underlying engine map.

The following example briefly illustrates how this process works. As described above, combinations of technologies are modeled as a complete vehicle system. Take, for example, a technology package consisting of a combination of variable valve timing, cylinder deactivation, and 6-speed automatic transmission technologies. For a specific vehicle platform, each technology individually offers a reduction in CO_2 emissions as presented below in Table 2-7 (which, in this case, reflects modeling for the large car class). However, when modeled in combination, the package provides a reduction that is somewhat less than the sum of the individual technology benefits. The reason for this is that each of the three technologies reduces a portion of the throttling loss encountered at part loads (when the engine is pumping against a partially closed throttle). Once a portion of the loss has been addressed by one technology, that loss has been eliminated and cannot be reduced by another technology.

Table 2-7: Comparison of Individual versus Combination Benefits

Technology	Individual CO_2 Emissions Impact (%)
Dual Cam Phaser	-4.3
Cylinder Deactivation	-6.2
6-Speed Automatic	-2.8
Combination Impacts	
Combination Total (Additive)	-13.3
Combination Total (Multiplicative)	-12.7
Actual Simulated Combination Impact	-10.8

Dual cam phasing allows engine load to be reduced by increasing valve overlap and internal EGR rather than by closing the throttle. As a result, CO_2 emissions are reduced in the partial-load region. At this same speed and load point, a large-car engine equipped with dual cam phasing emits 4.3 percent less CO_2 than an engine not equipped with the technology.

Cylinder deactivation reduces CO_2 emissions by deactivating half of the engine cylinders at operating points where desired power can be met with a reduced displacement engine. This forces the cylinders that remain active to operate at higher load, requiring less throttling (and lower losses). For example, to provide the same output as the dual cam phaser equipped engine operating at 1914 rpm (revolutions per minute) and 2.48 BMEP (brake mean effective pressure), the deactivated engine operates at about 1877 RPM and 3.27 bar BMEP. This higher average operating load results in about 6 percent less CO_2 emitted over the FTP75 cycle.

A 6-speed automatic transmission reduces CO_2 emissions by offering more transmission gear ratios, thereby allowing engine speed and load to be shifted towards more efficient operating points while maintaining constant power. This is similar to the benefits for an engine operating with deactivated cylinders, but occurs in all modes of operation. Compared to the baseline large car, a vehicle equipped with a 6-speed automatic reduces CO_2 emissions by about 3 percent on the FTP75 cycle.

Combined Package Benefits – Since the 6-speed transmission and cylinder deactivation technologies both shift engine operating points toward higher loads, it is important to note the effect of the load shift on engine CO_2 emissions. At the higher load condition, the dual cam phaser equipped engine emits about 3 percent less CO_2 than the baseline engine versus 4.3 percent for the cam phaser technology considered alone (as presented in Table 2-7). This reduction in CO_2 emissions impact is due to the fact that at higher loads, the CO_2 emissions difference for the two engines becomes less pronounced. Furthermore, although the 6-speed automatic and cylinder deactivation technologies both shift engine operating load higher, the shifts are not additive. This effect, plus the reduced benefit for the dual cam phaser equipped engine at higher loads, explains the difference between the sum of the individual technology benefits and the benefits of those same technologies considered as a package.

2.5. Assessment of Additional Technologies

A number of additional technologies were evaluated using a combination of CRUISE simulations and available literature data. These include: low rolling resistance tires, low viscosity lubricating oil, early torque converter lockup, vehicle mass reduction, engine friction reduction, aerodynamic drag reduction, aggressive shift logic, air conditioning technology impacts, and hybrid vehicle technology.

For low rolling resistance tires, aerodynamic drag reduction, and vehicle mass reduction, AVL developed impact estimates (expressed as coefficients defining the percent CO_2 reduced per percent change in the associated force coefficient) through simulation using CRUISE for the small car and large truck categories.[26] Based on these coefficients together with estimates of associated reductions in rolling resistance and aerodynamic drag forces taken from existing technical literature, a conservative estimate of potential CO_2 reductions was developed for each of these technologies. Limited simulations of these technologies by AVL indicates that when applied in a constant performance scenario, substantial engine downsizing may be possible, so that the derived impact coefficients present a very conservative picture of the overall CO_2 reductions possible.

Literature data were used to assess the CO_2 reduction potential of early torque converter lock-up, aggressive shift logic, engine friction reduction, and improved lubricating oil. In all cases, a small fraction of the maximum potential benefits for each option was assumed in ascribing CO_2 reduction benefits to these technologies. This was done to avoid ascribing too large a benefit to technologies not fully evaluated through simulation modeling. In addition, for early torque converter lock-up and aggressive shift logic, a conservative approach was taken in recognition of the potential driveability issues associated with early upshifting and associated drivetrain harshness and vibration. However, it should be recognized that reductions considerably larger than those assumed in this study may be possible.

Table 2-8 provides a summary of the CO_2 emissions reduction estimated for each of these technologies. For each technology package modeled by AVL, an additional CO_2 reduction was assumed for the application of some or all of the technologies described above. For vehicles with automatic transmissions and automated manual transmissions, a 5 percent reduction was applied. For vehicles with continuously variable transmissions a 4 percent CO_2 reduction was applied. Finally, cost estimates for these additional technologies (as shown in Table 2-8) were developed using the same literature review. Given that a range of estimates for both CO_2 reduction and cost was generally provided in the literature, a methodology to develop a single CO_2 reduction and cost estimate was required. To resolve these data, the median of the combined estimated cost range for all technologies was divided by the median of the combined estimated CO_2 reduction range to derive an estimated cost per percent CO_2 reduction. This median estimate was

[26] Average coefficients are as follows: 0.2 percent CO_2 reduction per percent aerodynamic drag or rolling resistance reduction; 0.6 percent CO_2 reduction per percent mass reduction.

developed both with and without mass reduction technology to allow for the separate treatment of mass reduction. Since mass reduction was not investigated as a major CO_2 reduction technology in the study, the estimated unit cost without mass reduction was then multiplied by the assumed CO_2 reduction indicated in Table 2-8 to derive the total estimated marginal price of a combination of these technologies achieving the targeted CO_2 reduction. Actual marginal price could be higher or lower depending on the specific combination of technology chosen for implementation. This estimated marginal price was added to the incremental vehicle cost for all scenarios in which these additional technologies were assumed. As stated, the additional technologies package did not include weight reduction, although information on weight reduction is included in the table.

2.5.1. Air Conditioning

An independent evaluation of the impacts of vehicle air conditioning systems on vehicle CO_2 and HFC emissions was conducted by Meszler Engineering Services (MES). In this evaluation, the results of which are included as Appendix D of this study, MES evaluated the magnitude of GHG emissions that result from air conditioning systems due to both the increased load placed on a vehicle engine and refrigerant leakage. To incorporate the results of this evaluation into the simulation modeling conducted by AVL, MES developed representative air conditioning load curves for air conditioning systems typical of current vehicle technology and increased efficiency technology. For purposes of this analysis, the assumed baseline system is an HFC-134a system utilizing a pneumatically (freeze point) controlled fixed displacement compressor, while the increased efficiency system is an HFC-152a system utilizing an externally controlled variable displacement compressor and forced air recirculation. Both load curves were developed to be representative of typical ambient conditions experienced during air conditioning operation in the U.S.

To evaluate the impact of air conditioning use, AVL performed a series of simulations in which baseline air conditioning loads were added to the normal loads encountered over the study driving cycles. The additional CO_2 emissions that result from air conditioning use were added to the baseline CO_2 emissions predicted by CRUISE modeling for a corresponding technology scenario without air conditioning. A second simulation was then conducted with the alternative (i.e., externally controlled variable displacement) air conditioning system to determine the CO_2 reduction impact. It should be recognized that under either air conditioning scenario, CO_2 emissions are greater than the corresponding scenario without air conditioning, so that the benefits of improved air conditioning systems cannot be subtracted from a "no air conditioning" scenario. It should also be recognized that the effect of refrigerant leakage is independent of vehicle operation and does not affect the CO_2 emissions predicted by CRUISE. As a result, while benefits associated with reduced leakage have been calculated as described in the MES report in Appendix D, these benefits do not show up in the simulation modeling. Reduced leakage benefits are incorporated into the simulation results by adding the estimated per-mile changes in refrigerant leakage rates, expressed as CO_2 equivalent emissions, to the CRUISE-generated CO_2 emission estimates.

Table 2-8: Impacts and Costs of Additional CO_2 Reduction Technologies

Technology		Transmission Type		
		Automatic	Automated Manual	CVT
Improved Tires	Impact	10% reduction in rolling resistance = 2% reduction in CO_2		
	Cost	\$20 to \$90 retail price equivalent (RPE)		
Engine Friction Reduction or Improved Lubricating Oil	Impact	Reduced internal friction/lower viscosity oil, 0.5% CO_2 reduction		
	Cost	\$5 to \$15 RPE		
Aerodynamic Drag Reduction	Impact	8-10% reduction in drag = 1.5-2% reduction in CO_2		
	Cost	\$0 to \$125 RPE		
Aggressive Shift Logic	Impact	1.5% CO_2 reduction	0.5% CO_2 reduction	None
	Cost	\$0 to \$50 RPE	\$0 to \$20 RPE	
Improved Torque Converter or Early Lockup	Impact	0.5% CO_2 reduction	None	
	Cost	\$0 to \$10 RPE		
Weight Reduction	Impact	5% reduction in mass = 3% reduction in CO_2		
	Cost	\$180 to \$300 RPE		
Total Potential (without Weight Reduction)	Impact	6% to 6.5% CO_2	4.5% to 5% CO_2	4% to 4.5% CO_2
	Cost	\$25 to \$290 RPE	\$25 to \$250 RPE	\$25 to \$230 RPE
Total Potential (with Weight Reduction)	Impact	9% to 9.5% CO_2	7.5% to 8% CO_2	7% to 7.5% CO_2
	Cost	\$205 to \$590 RPE	\$205 to \$550 RPE	\$205 to \$530 RPE
Average RPE per Percent CO_2	w/o WR	\$25	\$29	\$30
	w/ WR	\$43	\$49	\$51
Assumed Improvement	Impact	5% CO_2 reduction	5% CO_2 reduction	4% CO_2 reduction
	Cost	\$125 RPE	\$145 RPE	\$120 RPE

Notes: (1) Impacts and costs are based on estimates from available data which is summarized in Chapter 3 and detailed in Appendix B.

(2) Torque converter improvement estimates from *Documentation of Technologies Included in the NEMS Fuel Economy Model for Passenger Cars and Light Trucks*, Energy and Environmental Analysis, Inc., 2002.

(3) Simulation modeling by AVL for this study established CO_2 percent per percent change coefficients of 0.2 for rolling resistance and aerodynamic drag reduction and 0.6 for mass reduction.

2.5.2. Methane and Nitrous Oxide Emissions

An independent evaluation of methane and nitrous oxide emissions was also conducted by MES. In this evaluation, the results of which are included as Appendix E, MES evaluated the GHG emissions contributions of methane and N_2O from both current and future (i.e., 2009-2015) vehicles. Current emission rates were estimated on the basis of actual emissions test data; these data were also used to derive relationships between methane and other organic compound emissions and between N_2O and NO_x emissions. Expected future emission rates of methane and N_2O were then developed by applying these relationships to expected future emission rates of organic compounds and NO_x.

2.5.3. Hybrid Vehicle Assessment

As described above, the benefits of mild-hybrid (i.e., 42 Volt ISG) technology were evaluated using the CRUISE simulation code. However, the level of effort required to construct and validate CRUISE control modules for more advanced, combination internal combustion engine and motor drive systems was prohibitive. Therefore, the impacts of what we call "motor assist" and "fully integrated" hybrid technology were estimated using current vehicle certification data in combination with technology cost estimates developed for this study. The use of certification data to estimate CO_2 impacts is beneficial in that the derived impacts are based on actual production vehicle data, but this approach may be conservative in that it assumes no additional technology improvements between now and 2009-2015.

The impacts of motor assist hybrid vehicle technology are based on the 2004 Honda Civic Hybrid, which employs parallel hybrid technology using a 10 kW permanent magnet motor. The impacts of the fully integrated hybrid vehicle technology are based on the 2004 Toyota Prius, which employs combination series/parallel hybrid technology using a 50 kW permanent magnet motor and a 30 kW generator. Both vehicles generate the bulk of their CO_2 emission reduction impacts through three primary mechanisms:

- A reduction in internal combustion engine size, allowing a wider range of operations to be accomplished in regions of high efficiency.
- The capture, storage, and reuse of braking energy.
- The deactivation of the internal combustion engine during periods of vehicle deceleration and stopping.

However, both the Civic and Prius also incorporate additional technologies that contribute to CO_2 reduction impacts, while adding to incremental costs. Thus, neither vehicle can be considered in the context of its power electronics alone, since when viewed as a package (as is the case in this study) both vehicles include non-electronic technologies not generally found on other conventional vehicles.

The package of technologies that constitute the Civic and Prius can only be established relative to a specific conventional vehicle. Ideally, the comparative vehicle will employ technologies consistent with those of the specific vehicle class of which it is a component. While there are non-hybrid Civics that could serve as a point of comparison, conventional Civics generally employ technology that is somewhat more advanced than average small car technology. Since accounting for the impacts of these "non-average" technologies further complicates the comparative process, the conventional Civic is not used as a comparative basis in this study. The Prius has no direct conventional counterpart.

In addition to the basic technology consistency criteria, determining the CO_2 reduction impacts of hybrids from vehicle certification data also demands a comparative vehicle that has a 25-50 percent larger engine displacement and performance characteristics similar to that of the comparative hybrid. The engine displacement offset is desirable to provide a comparative vehicle that would be similar in displacement to the hybrid vehicle if the conventional vehicle were converted to hybrid with its accompanying engine downsizing. The equivalent performance requirement is intended to ensure that the conventional and hybrid vehicles are approximately equal from a consumer utility standpoint.

Based on these criteria the conventional vehicle selected for comparison to the Toyota Prius was the 2004 2.4-liter 4-cylinder automatic transmission Toyota Camry. At 1.5-liters, the engine displacement of the Prius is about 38 percent lower. The Camry accelerates from 0-60 mph in about 9.2 seconds, while Prius is a bit slower at about 10 seconds. With a difference of less than 10 percent, this is superior to other comparative alternatives in the large car class. Nevertheless, it should be recognized that there is a small performance loss associated with the resulting CO_2 impact estimates. Compared to the Camry, the Prius emits about 53 percent less CO_2 per mile (approximately 158 grams per mile compared to 333 grams per mile). Therefore, the CO_2 reduction impact of the fully integrated hybrid is estimated to be 53 percent in this study.

In addition to the introduction of the basic hybrid components (i.e., batteries, motor, generator, inverter, and control system), the Prius also exhibits the following technology differences relative to the Camry. It has a drag coefficient that is approximately 10 percent lower, at 0.26 versus 0.28. It has a curb weight that is approximately 300 pounds lower, at 2,900 pounds versus 3,200 pounds. This weight difference is in addition to the estimated 290 pounds required to offset the introduction of the hybrid electronic system. Thus, a total weight offset of 590 pounds is required to generate Prius-type CO_2 emission improvements relative to the base Camry. In cases where associated engine downsizing would result in a reduction in cylinder count, there is an associated weight savings estimated to be approximately 150 pounds. This savings would accrue for 6 and 8 cylinder vehicles converted to hybrid power, as each is assumed to drop 2 cylinders in moving to 4 and 6 cylinder internal combustion engines respectively. Since vehicle and technology weight will vary by vehicle class, the estimated weight reduction to produce CO_2 reductions at the estimated rate (i.e., 53 percent) is best expressed algebraically as:

$$\text{Weight Reduction} = \left[1 - \frac{\text{Prius Weight}}{\text{Camry Weight}}\right]\left(\text{Base Conventional Weight}\right) + \text{Electronics/Battery Weight} - \text{Downsizing Weight Savings}$$

Finally, to facilitate the attainment of the estimated 53 percent CO_2 reduction rate across each of the five vehicle classes investigated in the study, the electronics and batteries employed in the Prius were resized for each vehicle class in accordance with the ratio of the class average rated horsepower to the rated horsepower of the Camry. This results in larger electronic systems for the large car, small truck, large truck, and minivan classes and a smaller system for the small car class. On the basis of these adjustments, the following weight reduction requirements were estimated for the study classes:

- Small Car .... 530 pounds
- Large Car .... 490 pounds
- Small Truck ..... 520 pounds
- Large Truck ..... 690 pounds
- Minivan .... 590 pounds

It is perhaps important to emphasize three issues related to the estimated weight reductions. First, a substantial portion of the estimated reduction is associated not with downsizing, but with offsetting the added weight of the electronic components. A small (less than 10 percent) weight reduction results from the fact that the estimated CO_2 reduction was determined relative to the 2.4-liter Camry, which is heavier than the Prius. Second, the weight reduction required in the small car class is higher than that for the large car class because the weight advantage of engine downsizing is essentially unavailable in the small car class. Finally, even though the Prius is in the large car class as defined in this study, its CO_2 impacts were assessed relative to the 2.4-liter Camry that is substantially underpowered relative to the large car class average. Thus, the fully integrated hybrid evaluated for the large car class was upsized relative to the 2004 Prius.

Each of these technology differences is accounted for in the associated cost estimates for the fully integrated hybrid, using the technology-specific incremental cost impact described in the previous sections. In addition, the Prius includes an electronic CVT, but this cost is subsumed in the power electronics cost estimates presented below. Additional costs are also imposed for an intake cam phaser required to allow internal combustion to take place over the Atkinson/Miller cycle, as well as for electronic power steering and electric accessories (which were employed in all hybrid vehicle scenarios in this study).

The motor assist hybrid impact and cost estimates developed for this study essentially adhere to an analogous approach conducted for the Honda Civic Hybrid. The conventional vehicle selected for comparison to the 2004 Civic was the 2004 2.2-liter 4-cylinder automatic transmission Chevrolet Cavalier. At 1.34-liters, the engine displacement of the Civic Hybrid is about 40 percent lower. The Cavalier accelerates from 0-60 mph in about 8.2 seconds, while Civic is over 35 percent slower at about 11.3 seconds. Due to this substantial difference, an additional adjustment was employed in the motor assist hybrid analysis that increased the output (i.e., size) of the Civic electronics in accordance with the horsepower ratio of the Cavalier to the Civic. This results in a 50 percent upsizing of the Civic electronic system (and adds additional weight that must be offset to maintain the estimated CO_2 reduction), and is expected to bring the acceleration performance into better agreement with the Cavalier. However, as was the case with the

Prius, it is likely that there is a small performance loss that accompanies the resulting CO_2 impact estimates. Compared to the Cavalier, the Civic emits about 45 percent less CO_2 per mile (approximately 185 grams per mile compared to 334 grams per mile). Therefore, the CO_2 reduction impact of the motor assist hybrid is estimated to be 45 percent in this study.

As was the case with the Prius, the Civic also exhibits non-hybrid technology differences relative to the Cavalier. It has a drag coefficient that is approximately 20 percent lower, at 0.28 versus 0.36. The curb weights of the two vehicles are approximately equal, at 2,660 pounds (Civic) versus 2,680 pounds (Cavalier), but weight reduction is still required to offset the introduction of the hybrid electronic system. However, relative to weight offsets estimated for the Prius, the required offsets for the Civic are significantly smaller and in cases where the associated engine downsizing would result in a reduction in cylinder count, the estimated weight savings of approximately 150 pounds continues to apply. Since vehicle and technology weight will vary by vehicle class, the estimated weight reduction to produce CO_2 reductions at the estimated rate (i.e., 45 percent) is best expressed algebraically as:

$$\text{Weight Reduction} = \left[1 - \frac{\text{Civic Weight}}{\text{Cavalier Weight}}\right](\text{Base Conventional Weight}) + \text{Electronics/Battery Weight} - \text{Downsizing Weight Savings}$$

To facilitate the attainment of the estimated 45 percent CO_2 reduction rate across each of the five vehicle classes investigated in the study, the electronics and batteries employed in the Civic were resized for each vehicle class in accordance with the ratio of the class average rated horsepower to the rated horsepower of the Cavalier. This results in larger electronic systems for the large car, small truck, large truck, and minivan classes. On the basis of these adjustments and the performance adjustment previously described, the following weight reduction requirements were estimated for the study classes:

- Small Car .... 200 pounds
- Large Car .... 90 pounds
- Small Truck ..... 90 pounds
- Large Truck ..... 140 pounds
- Minivan .... 90 pounds

Once again, it should be emphasized that the estimated weight reduction is associated not with downsizing, but with offsetting the added weight of the electronic components. As with the Prius, the weight reduction required in the small car class is higher than that for the large car class because the weight advantage of engine downsizing is unavailable in the small car class. Finally, due to the electronics upsizing adjustment intended to improve the performance of the Civic relative to the Cavalier, even the motor assist hybrid system for small car class (of which the Civic is a part) is upsized relative to the 2004 Civic.

Like the Prius, each of these technology differences is accounted for in the associated cost estimates for the motor assist hybrid, using the technology-specific incremental cost impacts described in the previous sections. The Civic Hybrid includes a CVT, but this cost is included along with the power electronics cost estimates in the package costs presented below and is, therefore, not costed separately. Additional costs are, however, incurred for a discrete variable valve lift system with intake cam phasers to facilitate the lean burn combustion characteristics of the Civic, as well as for electronic power steering and electric accessories (which were employed in all hybrid vehicle scenarios in this study).

2.6. Cost-Benefit Analysis

For each of the technology packages described above, an incremental vehicle cost was determined and is presented in the results section (Chapter 3). Since the Martec costs were reported as costs to the manufacturer, a conversion of the Martec data to retail price equivalent was performed. To convert the Martec costs, NESCCAF used a retail price equivalent mark-up of 40 percent based on the RPE used in the 2002 National Academy of Sciences study.[27]

Using incremental vehicle costs, a cost-benefit analysis was performed for each of the technology packages. In addition to incremental vehicle cost, this analysis takes into account the savings realized through reduced fuel-use over the life of the vehicle. Lifetime cost-savings were estimated using two possible gasoline prices: (1) the 2003 U.S. average gasoline price of $1.58 per gallon available from the Energy Information Administration[28] and (2) a higher price of $2.00 per gallon. Further assumptions used in this analysis included:

- vehicle life of 12 years
- 15,600 miles traveled in the first year, declining 4.5% each year thereafter[29]
- a 5% discount rate for the net present value (NPV) fuel savings calculation

The next Chapter provides final results for the cost-benefit as well as emissions reduction portions of the analysis

[27] National Academy of Sciences, "Effectiveness and Impact of Corporate Average Fuel Economy (CAFE) Standards," National Academy Press, 2002

[28] Energy Information Administration http://www.eia.doe.gov/oil_gas/petroleum/data_publications/wrgp/mogas_history.html

[29] U.S. Department of Transportation, 1995 National Personal Transportation Survey (NPTS) http://nhts.ornl.gov/2001/index.shtml

3. Results of Greenhouse Gas Emission Reduction Analysis

3.1. Overview

The methodological approaches described in Chapter 2 and detailed in Appendices A through E were used to predict the CO_2 emission impacts and costs associated with deploying a variety of automotive technologies on future light-duty motor vehicles. Potential reductions in emissions of methane and nitrous oxide were separately evaluated to provide for a full accounting of total GHG-reduction potential. In this report, technical feasibility results and costs are presented for five classes of vehicles: "large car," "small car," "minivan," "small truck/SUV," and "large truck/SUV."

A total of 35 engine, transmission, and vehicle technologies were evaluated in this analysis to quantify associated CO_2-reduction potential. Currently deployed gasoline engine technologies such as turbocharging and variable valve lift were evaluated as well as more advanced technologies such as camless valve actuation, gasoline homogeneous charge compression ignition, and automated manual transmissions. Hybrid electric drivetrains and advanced diesel engines were also considered. The emission benefits of both individual technologies and packages or combinations of these technologies were analyzed. The study relies on a systems analysis approach that avoids the "double counting" that could occur by simply combining the emission reduction benefits of individual technologies. Examples of the difference between additive benefits and more sophisticated systems benefits were presented in the method overview to illustrate the impact of the systems analysis approach on emission benefit projections.

The technologies evaluated in this study are described in Appendix A. This Chapter first discusses the CO_2-reduction potential of individual technologies. The overall GHG impact and retail price equivalent cost estimates are then presented for each of the technology packages evaluated. Given the challenges and uncertainties associated with projecting the costs of future technologies, the cost estimates developed for this analysis are also compared with those from other recent studies. A range of costs is provided for individual technologies since there is considerable variation across studies.

3.2. Emission Reduction Results

As described in Chapter 2, the emissions benefit analysis conducted for this study involved several steps. The first step was a literature survey and engineering assessment to identify potential GHG-reduction technologies and assess their likely emission reduction capabilities. Actual vehicle models from the U.S. fleet were selected to represent each of the five classes of light-duty vehicles evaluated in this study. The study employed AVL's CRUISE software program and other approaches to assess the GHG impacts of individual technologies for each vehicle class. Candidate technologies were ranked and those suitable for further analysis were identified. These included both stand-alone technologies and those appropriate for inclusion with other technologies in combination packages. A systems analysis was subsequently conducted for the selected technology packages. The results of these analyses are presented in the following sections.

3.2.1. GHG Emission Reduction Potential for Individual Technologies

Individual technologies were first evaluated to aid in the selection of options for inclusion in technology packages or combinations which were then subjected to more in-depth evaluation using the CRUISE simulation code (as described in detail in the methodology section). This initial evaluation was designed to provide approximate CO_2-reduction estimates for use solely in the context of selecting technologies for further investigation. The results of this analysis are presented in Appendix B.

Because this first part of the study served a preliminary screening function, not all technologies were evaluated using full model simulations. Therefore, in many cases the full benefits of individual technologies are not captured. For example, the benefits of technologies that both improve performance and lower GHG emissions may not be fully characterized since additional benefits available through engine downsizing are not necessarily reflected. Some technologies were evaluated using full CRUISE simulations, others using partial CRUISE simulations, and others using data from the published literature.[30]

Individual technologies produced a broad range of projected CO_2 reductions. The analysis indicates that evolutionary engine and drivetrain technologies generally provide reductions ranging from a few to ten percent. The technologies offering the most significant GHG reductions (13-27 percent) are diesel advanced multi-mode (partial HCCI) and direct injection diesel engines and hybrid electric drivetrains (42-53 percent reductions). Other technologies showing significant reduction potential are 42-volt ISG (5-10 percent); electrohydraulic camless valve actuation (11-16 percent); 6-speed automated manual transmissions (5-8 percent); turbocharging (6-8 percent); and variable valve lift (4-6 percent). The results for all technologies are reasonably consistent across the five vehicle classes.

Additional GHG-reduction benefits are also achieved through reduced emissions of methane (CH_4) and nitrous oxide (N_2O), as well as through reduced CO_2 emissions associated with air conditioner (A/C) operation. AVL conducted simulation modeling of an alternative A/C system design on the basis of a thorough analysis of the impacts of A/C system technology as described in Appendix D. Based on that analysis, AVL modeled the CO_2 emissions impacts of an HFC-152a system using an externally controlled, variable displacement compressor (VDC) and forced air recirculation relative to the emissions associated with a baseline HFC-134a system using a pneumatically (freeze point) controlled, fixed displacement compressor (FDC). It should be noted that CO_2 emissions for both systems are greater than emissions under an "A/C off" scenario, so that improved efficiency impacts accrue relative to an "A/C on" situation only. Because vehicle A/C is not used all the time, the impact estimates that are included in Tables 3-4 through 3-8 are adjusted to reflect the estimated average percentage of operation (in miles) that the A/C system is in use (34 percent as described in Appendix

[30] Single point (i.e., partial simulation) evaluations were conducted on technologies where the engine full load curve did not dramatically change with the introduction of a technology. This simplified approach was taken to allow for a greater number of full CRUISE simulations to be run during the technology package evaluation phase of the project.

D). Table 3-1 presents a summary of both the adjusted and unadjusted A/C system impacts that are included in the CO_2 emission estimates presented in Tables 3-4 through 3-8.

Table 3-1: Air Conditioning Emissions

Emissions Source	Vehicle Class	Baseline A/C System	Alternative A/C System	Emissions Change
Indirect Efficiency-Based Emissions (Not Adjusted for A/C "On" Time)	Small Car	49.5	22.7	-54%
	Large Car	56.1	25.7	
	Small Truck	69.2	31.8	
	Large Truck	69.2	31.8	
	Minivan	69.2	31.8	
Indirect Efficiency-Based Emissions (Adjusted for A/C "On" Time)	Small Car	16.8	7.7	
	Large Car	19.1	8.7	
	Small Truck	23.5	10.8	
	Large Truck	23.5	10.8	
	Minivan	23.5	10.8	
Indirect Mass-Based Emissions	All	1.7	1.5	-9%
Direct Leakage Emissions	All	8.5	0.4	-95%

Note: Indirect mass-based emissions are not included in Tables 3-4 through 3-8 since vehicle test weights, as simulated by CRUISE, include the weight of the A/C system.

3.2.2. Projected Cost of Technologies

As discussed in Chapter 2, this study employed a detailed approach to estimating the costs associated with various GHG-reducing technologies. Much of the cost information was drawn from inquiries made of automobile manufacturers and component suppliers. Costs developed using this approach are typically conservative and could overstate the actual cost that consumers will pay once the technologies are mass produced, since significant challenges and uncertainties are involved when projecting the actual cost of future technologies. To provide policymakers with the best available information, this section presents the RPE cost estimates developed using Martec's hardware cost projections for this study along with those of other recent studies. Table 3-2 compares the estimated retail price equivalents developed as part of this study for the large car class with cost projections from other recent studies. The cost estimates developed specifically for this study are presented in the column headed "study RPE." (In the case of diesel HCCI, a range is presented since the potential cost was subject to a greater level of uncertainty than typical of other costs.) Cost estimates from other recent studies are presented in the column headed "Literature RPE". In general, the estimates developed by Martec for this study are within the range of costs predicted by other studies.

Table 3-2: Comparison of Study RPE with Literature RPE

Technology	Study RPE	Literature RPE
Single Cam Phaser	$98	$18-$70
Couple Cam Phasers	$161	$35-$140
Dual Cam Phasers	$196	$35-$140
Discrete Variable Valve Lift with Intake Phasers	$259	$70-$495
Discrete Variable Valve Lift with Coupled Phasers	$322	$70-$495
Discrete Variable Valve Lift with Dual Phasers	$357	$70-$495
Continuous Variable Valve Lift with Intake Phasers	$483	$70-$495
Continuous Variable Valve Lift with Coupled Phasers	$546	$70-$495
Continuous Variable Valve Lift with Dual Phasers	$581	$70-$495
Electrohydraulic Camless Valve Actuation	$910	$280-$600
Cylinder Deactivation (DeAct)	$161	$112-$746
DeAct plus Discrete Variable Valve Lift with Intake Phasers	$378	$182-$1241
DeAct plus Discrete Variable Valve Lift with Coupled Phasers	$441	$182-$1241
DeAct plus Discrete Variable Valve Lift with Dual Phasers	$476	$182-$1241
Stoichiometric Gasoline Direct Injection	$259	$450-$750
Gasoline Homogeneous Charge Compression Ignition	$581	
High Speed Direct Injection Diesel	$1225	$1752-$2200
Diesel Homogeneous Charge Compression Ignition	$840 to $1050	
6-Speed Automatic Transmission	$105	$0-$280
Automated Manual Transmission	$0	$0-$280
Continuously Variable Transmission	$245	$0-$398
42 Volt System (Idle Off, Regen Braking, Launch Assist)	$1582	$280-$1400
Motor Assist Gasoline Hybrid Electric Vehicle	$2709	$1364-$3036
Fully Integrated Gasoline Hybrid Electric Vehicle	$5299	$3184-$5183
Electric Accessories	$70	$50
Electric Power Steering	$56	$40-$150
Turbocharging	$-420	$350-$837
Improved Alternator	$56	$15

Table 3-3: Estimated Costs of California's Low Emission Vehicle (LEV) Program

Vehicle	CARB '94	CARB '96	ACG '93	AAMA '94	Actual
TLEV	$66	$72	$273	$298-487	$35
LEV	$120	$120	$788	$911-1343	$83
ULEV	$227	$145	$679-1,326	$1,666-4,005	$251

Sources: The CARB and AAMA (American Automobile Manufacturers Association) figures are taken from Cackette, 1998; the ACG (Automotive Consulting Group) figures are found in ACG, 1993.

As mentioned above, cost almost always represents an area of large uncertainty and debate because some of the technologies needed to comply with the standards have not yet been commercialized. Historically, cost estimates are generally more conservative and higher than actual costs, which usually prove to be lower than first anticipated.

For example, Table 3-3 compares per-vehicle cost estimates at various points in time from CARB and various industry sources for California's different categories of low-emission vehicles. These projections can be compared against the actual implementation costs shown in the last column to the right.

As shown in Table 3-3, industry estimates of compliance costs were an order of magnitude higher than actual costs. Similarly, the cost projections made by CARB also overstated the actual cost of complying with the LEV standards, although by a much smaller margin.

3.2.3. GHG Emission Reduction Potential for Technology Combinations

Based on their GHG reduction potential and, in part, on the costs of the technologies shown above, technology combinations or packages were developed for each of the five vehicle classes evaluated in this study. The emission impacts of these technology packages were then evaluated using full CRUISE vehicle simulations. Ultimately, a total of 75 simulation runs were completed for the five model vehicles developed to represent each vehicle class.

The emissions reductions attributable to A/C system improvements and a package of other technologies (including low rolling resistance tires, engine friction reduction, and other improvements) were incorporated into the reduction estimates for modeled technology packages. The A/C improvements added a 3-4 percent CO_2 reduction benefit, depending on the CO_2 emissions of the vehicle when the A/C was off; the other upgrades added a 4-5 percent CO_2 reduction to non-hybrid technology packages.

While the selection of technology packages was made, in part, from a cost-effectiveness standpoint, a broad spectrum of technologies were included in the modeled packages regardless of cost, to ensure that the full range of potential CO_2 reduction options was evaluated. All of these results (not just the least-cost results) are provided in the following sections. Tables 3-4 through 3-8 present the combined model simulation, A/C, and additional technology benefits. The results of the AVL simulation modeling for each package are provided separately in Appendix B, without the A/C and additional technology benefit adjustments.

Similar technology packages were evaluated for each of the five categories of vehicles. The results of the analysis show that deployment of technologies across all five vehicle classes achieves comparable CO_2 reductions. There are, however, some exceptions; these are detailed in the discussions of the individual vehicle categories below. To illustrate this point, the technology package including stoichiometric gasoline direct injection, cam phaser, turbocharging, and automated manual transmission technology was evaluated in four categories of vehicles—in each, this particular technology combination provides between a 27 percent and 30 percent CO_2 reduction. Another example: the package including discrete variable valve lift, dual cam phaser, and automatic transmission[31] technology was evaluated for all five vehicle classes and was estimated to provide a 12-18 percent CO_2 reduction in each case. The largest number of technology packages was evaluated for the large car category. While some of these technology combinations were not evaluated for vehicle classes other than large cars, the consistency of results across vehicle classes suggests that similar CO_2 reductions would likely be achieved with the deployment of the same technology packages in other classes.

Large Car Results

Table 3-4 presents emission reduction and cost estimates for the 19 technology packages modeled for the large car class. Column 1 lists the technologies included in each combination package. Column 2 provides the combined city/highway CO_2 emissions rate, in grams per mile (g/mi), of the modeled package. Column 3 lists the percent CO_2 reduction relative to the 2002 baseline technology package. Column 4 lists the estimated retail incremental vehicle cost associated with the addition of these technologies. Column 5 indicates the net cost of the technology package, defined as incremental technology cost minus lifetime fuel savings.[32] The net cost analysis assumes a price of $1.58 per gallon for both gasoline and diesel. Last, Column 6 shows net cost per avoided ton of CO_2 emissions. Note that a negative net cost means that fuel savings more than offset the incremental cost of the emissions reduction technologies being modeled. In other words, it equates to projected consumer savings over the lifetime of the vehicle.

Emission reduction estimates range from 14-54 percent, relative to the 2002 baseline vehicle, for the 19 large car technology packages modeled. According to this analysis, combinations of technologies already used in some production gasoline models can reduce CO_2 emissions by approximately 25 percent. Examples of these technologies include 6-speed automatic transmissions, variable valve lift and timing, and cylinder deactivation. Reductions beyond this level will require the introduction of more advanced technologies such as gasoline direct injection, 42-volt starter generators, and diesel engine technology. For example, the combination of gasoline direct injection and 42-volt technology, along with turbocharging and advanced cam and transmission technology, can provide a 37 percent CO_2 reduction for an incremental vehicle cost of $1,700. Even greater CO_2 reductions can be achieved using hybrid-electric designs. It is critical to recognize that while the costs of using advanced technologies are somewhat greater than the cost of conventional gasoline technologies, fuel-cost savings to the owner over the life of the vehicle far outweigh the additional cost in all but the most aggressive technology packages. On a dollar per ton basis, the net cost of technology packages that produce up to 47 percent CO_2 reductions is negative, meaning that these packages result in net cost savings to the consumer over the lifetime of the vehicle.

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[31] Five or 6-speed automatic transmission was assumed, depending on the vehicle.

[32] This analysis assumes the vehicle life to be 12 years and 150,000 miles. More detail on the analysis and assumptions are provided in Chapter 2 on methods.

Table 3-4: Large Car GHG Reduction Results for Combinations of Technologies

(1) Technology Combinations	(2) CO_2 (g/mi)	(3) CO_2 Change (percent)	(4) Marginal Vehicle Cost ($)	(5) Net Cost ($)	(6) Net Cost ($ per ton CO_2)
Dual Cam Phasers, 6-Speed Automatic Transmission	305.4	14.4%	479	-438	-52
Dual Cam Phasers, Continuously Variable Transmission, Electric Power Steering, Improved Alternator	304.4	14.6%	725	-217	-25
Discrete Variable Valve Lift, Dual Cam Phasers, 6-Speed Automatic Transmission	300.3	15.8%	640	-393	-42
Continuous Variable Valve Lift, Dual Cam Phasers, 6-Speed Automatic Transmission	291.4	18.3%	864	-358	-33
Dual Cam Phasers, Cylinder Deactivation, 6-Speed Automatic Transmission	288.1	19.2%	640	-642	-57
Dual Cam Phasers, Turbocharging, 6-Speed Automatic Transmission, Electric Power Steering, Improved Alternator	280.3	21.4%	73	-1,386	-110
Gasoline Homogeneous Charge Compression Ignition, Discrete Variable Valve Lift, Intake Cam Phasers, Automated Manual Transmission, Electric Power Steering, Improved Alternator	273.8	23.2%	1,149	-444	-32
Continuous Variable Valve Lift, Dual Cam Phasers, Automated Manual Transmission, Electric Power Steering, Improved Alternator	266.3	25.3%	890	-857	-57
Stoichiometric Gasoline Direct Injection, Cylinder Deactivation, Dual Cam Phasers, Automated Manual Transmission, Electric Power Steering, Improved Alternator	266.2	25.4%	925	-829	-55
Cylinder Deactivation, Discrete Variable Valve Lift, Coupled Cam Phasers, 6-Speed Automatic Transmission, 42 Volt Integrated Starter/Generator, Electric Power Steering, Electric Accessories	261.1	26.8%	2,432	554	35
Stoichiometric Gasoline Direct Injection, Dual Cam Phasers, Turbocharging, Automated Manual Transmission, Electric Power Steering, Improved Alternator	252.5	29.2%	176	-1,868	-109
Electrohydraulic Camless Valve Actuation, Automated Manual Transmission, Electric Power Steering, Improved Alternator	252.0	29.3%	1,219	-841	-49
Diesel Homogeneous Charge Compression Ignition, Automated Manual Transmission, 42 Volt Integrated Starter/Generator, Electric Power Steering, Electric Accessories	248.6	30.3%	2,780	-41	-2
Electrohydraulic Camless Valve Actuation, Stoichiometric Gasoline Direct Injection, Automated Manual Transmission, Electric Power Steering, Improved Alternator	243.4	31.8%	1,478	-759	-41
Gasoline Homogeneous Charge Compression Ignition, Discrete Variable Valve Lift, Intake Cam Phasers, Automated Manual Transmission, 42 Volt Integrated Starter/Generator, Electric Power Steering, Electric Accessories	232.8	34.7%	2,745	274	13
Stoichiometric Gasoline Direct Injection, Turbocharging, Dual Cam Phasers, 6-Speed Automatic Transmission, 42 Volt Integrated Starter/Generator, Electric Power Steering, Electric Accessories	225.3	36.8%	1,858	-775	-36
Motor Assist Gasoline Hybrid	189.9	46.7%	2,797	-609	-22
Fully Integrated Diesel Hybrid	163.0	54.3%	7,543	3,105	97
Fully Integrated Gasoline Hybrid	162.7	54.4%	5,387	1,391	43

As noted in Table 3-4, the emission reduction packages evaluated in this study include a wide range of individual technologies. Some of the most cost-effective packages include automated manual transmissions, turbocharging, stoichiometric gasoline direct injection, and camless valve actuation technology. Turbocharging, especially, proves to be a very cost-effective technology in the large car and other vehicle classes because it enables the manufacturer to downsize the vehicle engine and decrease engine cylinder count while maintaining equal performance. As previously noted, this study also assessed the GHG-reducing potential of technologies that are relatively expensive, in an effort to provide a robust overview of the benefits and costs of candidate CO_2 reduction technologies. Given that future technology advances could reduce costs for these technologies, the costs presented could be overstated. Consequently, the complete set of technology packages does not constitute a low cost solution to any particular CO_2 reduction scenario, but rather presents a host of possible solutions across a range of reductions and costs.

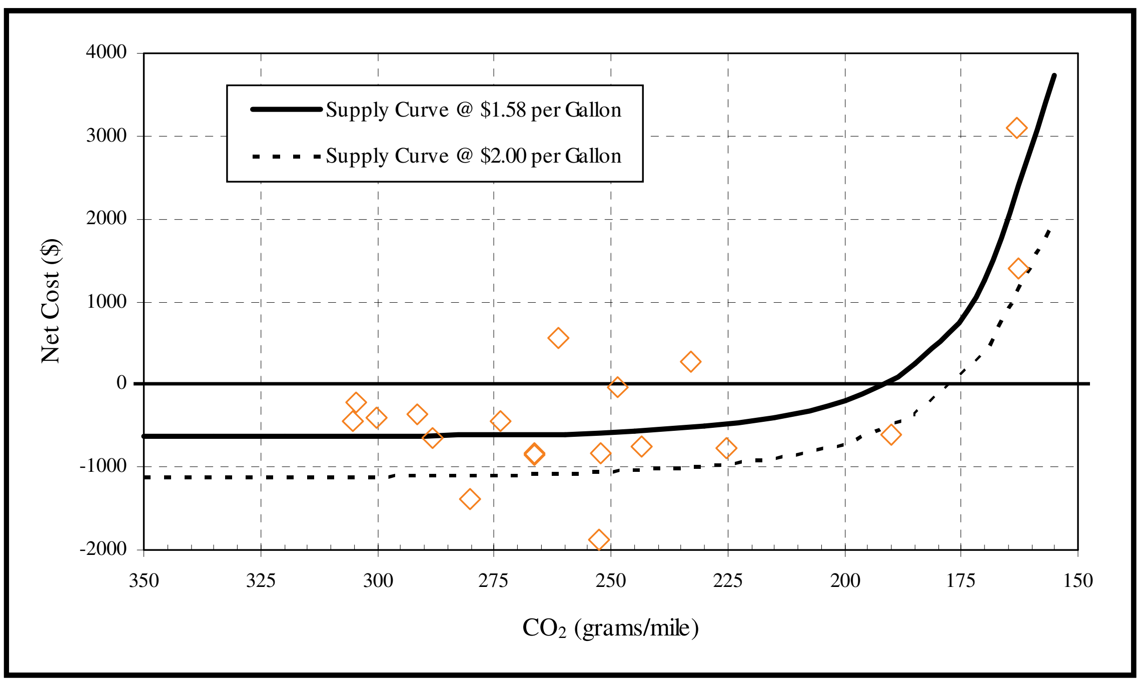
Figure 3-1 graphically depicts the relative benefits and costs of each of the evaluated technology packages. As this figure suggests, the technology packages span a broad range of reduction potentials and costs. For example, packages providing CO_2 reduction from 14 to 30 percent (emissions between 300 and 250 g/mi CO_2) encompass a net cost range from approximately negative $1,900 (i.e., net consumer savings) to positive $500 (i.e., net consumer cost). Clearly, a least-cost solution would favor the technology packages in the lower end of this cost range. Nevertheless, for purposes of this study, we have assumed a technology supply curve[33] that includes all of the evaluated technology packages. This allows for the fact that least-cost technologies may not be viable for some segments of the market and that vehicle manufacturers may therefore choose not to implement specific CO_2 reduction solutions across the entire vehicle class. For example, because technologies such as automated manual transmissions and turbocharging may be limited to a subset of the models in any class of vehicles, a supply curve constructed solely on the basis of least-cost solutions may understate the actual cost of a class-wide CO_2 reduction solution. Including all of the evaluated technology packages in the development of the supply curve provides a more robust indication of likely class-wide impacts.

The solid line in Figure 3-1 represents the CO_2 reduction supply curve for the large car class. As indicated, CO_2 reductions of about 45 percent (190 g/mi, relative to a 2002 vehicle at about 355 g/mi) are likely to be obtainable for a net negative cost (i.e. lifetime fuel savings exceed incremental technology costs). The figure also includes a second supply curve to show the results of a gasoline price sensitivity analysis in which the assumed prices of gasoline and diesel fuel are increased from $1.58 per gallon to $2.00 per gallon. At the higher fuel price, all but three of the technology packages reflect negative net costs, and the costs for two of those three are very nearly at the break-even point. A 42-volt cylinder deactivation package exhibits a net lifetime cost of $55, while the advanced gasoline hybrid-electric vehicle exhibits a net lifetime cost of $329. The advanced diesel hybrid still carries a net lifetime cost of about $2000. It is also important to recognize that the costs used to develop Figure 3-1 are those estimated specifically by

[33] For purposes of this study, a supply curve indicates the relationship between CO_2 emissions reduction potential and cost.

Martec for this study, as adjusted to reflect estimated retail equivalents. If the generally lower cost estimates of the other studies listed in Table 3-2 were considered, net costs would be further shifted to the negative. Nevertheless, as can be seen from the dashed line corresponding to $2.00 per gallon gasoline, vehicle owners can be expected to save $400-$1100 over the life of a vehicle achieving a CO_2 emissions rate of approximately 190 g/mi (this represents about a 45 percent reduction from an emissions rate of approximately 355 g/mi for the baseline 2002 vehicle). Assuming a lower gasoline price of $1.58, vehicle owners are estimated to save from $0 (i.e., no net cost) to $600 over the life of a vehicle for the same level of emission reduction. While diesel vehicles provide significant CO_2 reductions, the higher density of diesel fuel reduces the potential benefit of a given technology package relative to gasoline vehicles, especially as more aggressive carbon reduction scenarios are considered. For example, the two diamonds that are furthest to the right in Figure 3-1 represent the gasoline (lower cost diamond) and diesel (higher cost diamond) advanced hybrid cases. While the two cases provide very similar CO_2 reductions, the net costs for the diesel hybrid are about three times those of the gasoline hybrid (marginal vehicle costs are about 35 percent higher for the diesel vehicle). For less aggressive CO_2 reductions, diesel technology can be cost-effective as the CO_2 reductions associated with increased diesel engine efficiency are large enough to offset the additional cost. However, it should be recognized that much of the gasoline engine technology evaluated here is specifically designed to close the gap between gasoline and diesel engine efficiency.

Figure 3-1: Net Vehicle Costs for the Large Car Class Given Two Gasoline Price Scenarios



Small Car Results

Table 3-5 presents emission reduction and cost estimates for the 14 technology packages modeled for the small car class. Column 1 lists the technologies included in each combination package. Column 2 provides the CO_2 mass emissions rate of the modeled package. Column 3 lists percent CO_2 reductions relative to the 2002 baseline technology package. Column 4 lists the estimated retail incremental vehicle cost associated with the addition of these technologies, as estimated from hardware costs developed by Martec. Column 5 provides the net cost of the technology package, taking into account associated lifetime fuel savings.[34] As in the large car results discussed previously, the net cost analysis assumes a price of $1.58 per gallon for both gasoline and diesel fuel. Lastly, Column 6 displays net costs per ton of avoided CO_2 emissions. As before, a negative net cost figure equates to consumer savings over the lifetime of the vehicle as a result of fuel savings.

Emission reduction estimates range from 11-56 percent, relative to the 2002 baseline vehicle, for the 14 small car technology packages modeled. According to this analysis, combinations of technologies already used in some production gasoline models can reduce CO_2 emissions by approximately 23 percent. Examples of these technologies include 5 and 6-speed automatic transmissions and variable valve lift and timing. Reductions beyond this level will require the introduction of more advanced technologies such as gasoline direct injection and 12 or 42-volt idle off systems, which can provide a 29 percent CO_2 reduction for an incremental vehicle cost of approximately $1,000. Even greater CO_2 reductions can be achieved using advanced hybrid-electric designs. On a dollar per ton basis, the net cost of technologies producing CO_2 reductions of up to 29 percent is negative, indicating net cost savings to the consumer over the life of the vehicle.

As noted in Table 3-5, the emission reduction packages evaluated in this study include a wide range of individual technologies. Some of the most cost effective packages include automated manual transmissions, turbocharging, and stoichiometric gasoline direct injection. Because this class of vehicles uses smaller engines, the use of 12-volt idle off technology was explored as an option. The results suggest that this technology is likely to be very cost-effective for the small car class. Unlike the other vehicle classes, cylinder deactivation was not evaluated for the small car class due to the small size of the baseline engine. Compared to the large car class, the costs for achieving equivalent CO_2 reductions are somewhat higher for certain technologies. There are two reasons for this result. First, technologies such as turbocharging that allow for engine downsizing result in substantial cost reductions in the other vehicle classes as a result of cylinder count reductions. However, at four cylinders, the base engine in the small car class is at the minimum cylinder count considered to have broad market acceptability from a performance and engineering standpoint. Thus, engine downsizing in the small car class does not generate the same level of cost savings estimated for engine

[34] This analysis assumes the vehicle life to be 12 years and 150,000 miles. More detail on the analysis and assumptions are provided in Chapter 2 on methods.

Table 3-5: Small Car Results

(1) Technology Combinations	(2) CO_2 (g/mi)	(3) CO_2 Change (percent)	(4) Marginal Vehicle Cost ($)	(5) Net Cost ($)	(6) Net Cost ($ per ton CO_2)
Dual Cam Phasers, Continuously Variable Transmission, Electric Power Steering, Improved Alternator	270.9	10.6%	570	50	9
Dual Cam Phasers, Electric Power Steering, Improved Alternator	270.7	10.7%	360	-157	-29
Discrete Variable Valve Lift, Dual Cam Phasers, 5-Speed Automatic Transmission	264.9	12.6%	521	-122	-19
Dual Cam Phasers, 5-Speed Automatic Transmission, Electric Power Steering, Improved Alternator	261.8	13.6%	494	-216	-32
Dual Cam Phasers, 6-Speed Automatic Transmission	261.5	13.7%	346	-369	-54
Discrete Variable Valve Lift, Dual Cam Phasers, Automated Manual Transmission, Electric Power Steering, Improved Alternator	234.9	22.5%	465	-817	-72
Gasoline Homogeneous Charge Compression Ignition, Discrete Variable Valve Lift, Intake Cam Phasers, Automated Manual Transmission, Electric Power Steering, Improved Alternator	230.1	24.1%	841	-538	-45
Diesel Homogeneous Charge Compression Ignition, Automated Manual Transmission, 42 Volt Integrated Starter/Generator, Electric Power Steering, Electric Accessories	225.3	25.6%	3,643	1,533	119
Continuous Variable Valve Lift, Dual Cam Phasers, Automated Manual Transmission, 12 Volt Idle Off System, Electric Power Steering	217.9	28.1%	813	-830	-59
Stoichiometric Gasoline Direct Injection, Dual Cam Phasers, Turbocharging, Automated Manual Transmission, Electric Power Steering, Improved Alternator	216.1	28.7%	1,128	-547	-38
Gasoline Homogeneous Charge Compression Ignition, Discrete Variable Valve Lift, Intake Cam Phasers, Automated Manual Transmission, 42 Volt Integrated Starter/Generator, Electric Power Steering, Electric Accessories	205.7	32.1%	2,418	506	31
Motor Assist Gasoline Hybrid	160.4	47.1%	3,504	612	26
Fully Integrated Gasoline Hybrid	137.7	54.6%	5,639	2,248	82
Fully Integrated Diesel Hybrid	134.9	55.5%	7,690	3,858	139

downsizing in the other vehicle classes. Second, because the small car class has the lowest baseline CO_2 emissions and the lowest power to weight ratio of all the five classes, additional reductions accrue from a more aggressive baseline and carry somewhat higher costs

Figure 3-2 depicts the relative benefits and costs of each of the evaluated small car technology packages. As this figure suggests, the technology packages span a broad range of CO_2 reduction potentials and costs.[35] For example, packages providing CO_2 reductions from 14-30 percent (CO_2 emissions between 260 and 215 g/mi) encompass a net cost range from approximately negative $800 to positive $1,500. The estimated CO_2-reduction supply curve generated by this study considers this full range of results, rather than only the least-cost solutions. As noted, this approach is intended to allow for a more robust consideration of the benefits and costs of a full range of candidate CO_2-reduction technologies.

The solid line in Figure 3-2 represents the CO_2-reduction supply curve for the small car class. As indicated, CO_2 reductions of about 29 percent (from an emissions rate of 300 g/mi for a baseline 2002 vehicle to about 215 g/mi) are likely to be obtainable at net negative cost (i.e. with net lifetime savings). The figure also includes a second supply curve that reflects the results of a gasoline price sensitivity analysis in which the assumed prices of gasoline and diesel fuel are increased from $1.58 to $2.00 per gallon. At the higher fuel price all evaluated technology packages reflect negative net costs except the advanced hybrid vehicles and a 42-volt advanced multi-mode diesel technology package. As can be seen from the dashed line, at $2.00 per gallon of gasoline vehicle owners can be expected to save an average of about $300-$500 over the life of the vehicle while achieving a CO_2 emissions rate of approximately 210 g/mi (a 30 percent reduction from the 300 g/mi 2002 baseline). When gasoline prices of $1.58 are evaluated, vehicle owners will likely save from $0 (i.e., no net cost) to $250 over the life of a vehicle for the same level of emission reduction. As in the other vehicle classes, diesel vehicles provide significant CO_2 reductions but the higher density of this fuel reduces the potential benefit of most of the technology options evaluated relative to gasoline vehicles. A modestly expanded discussion of the cost of diesel CO_2 reductions is included in the section on large car results above.

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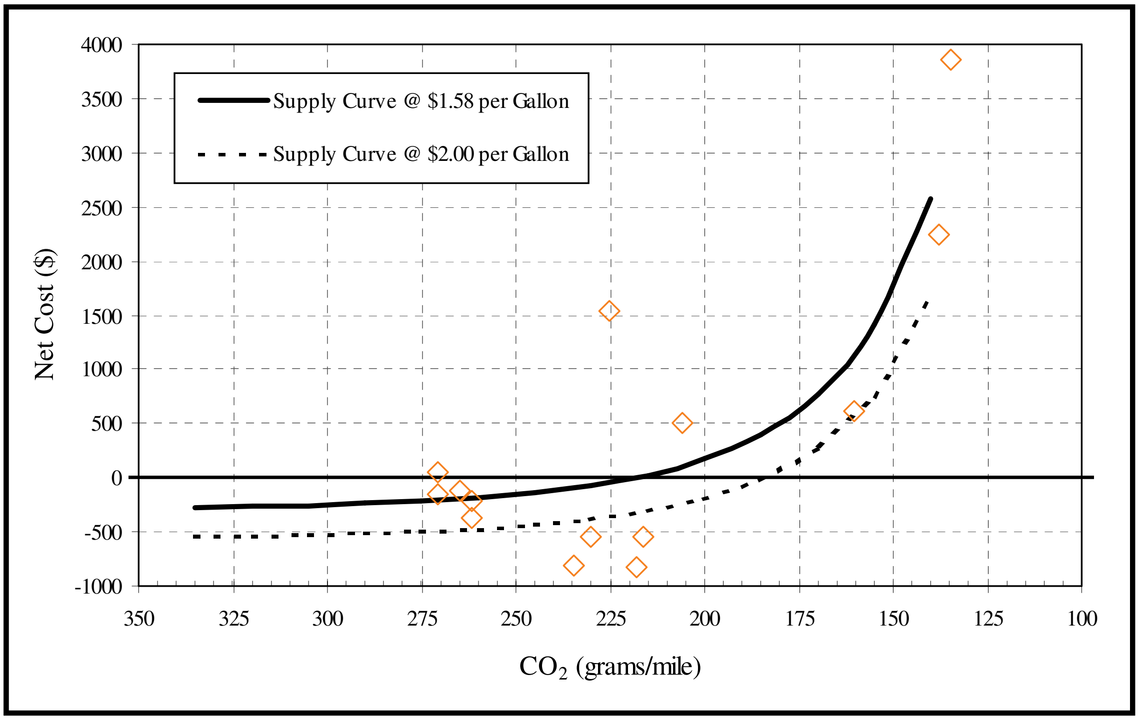
[35] As stated in the discussion for the large car class, this study intentionally focused on a broad range of technology packages that provide for an equally broad range of CO_2 reduction potentials and costs. Thus, the study has not attempted to consider only the least-cost solutions, but rather a broader range of solutions that might better reflect the cost of CO_2 reduction across the entire class of vehicles. While least-cost solutions might be appropriate for some segments of the class, other segments might require a somewhat more expensive solution to maintain a critical market distinction.

Figure 3-2: Net Vehicle Costs for the Small Car Class Given Two Gasoline Price Scenarios



Minivan Results

Table 3-6 presents emission reduction and cost estimates for the 14 technology packages evaluated for the minivan class. As in the previous sections, Column 1 lists the technologies included in each combination package; Column 2 gives the modeled combined city/highway CO_2 emissions rate; Column 3 shows percent CO_2 reductions relative to the 2002 baseline technology package; Column 4 shows estimated of incremental retail vehicle cost; Column 5 shows net lifetime costs including fuel savings at an average price of $1.58 per gallon for both gasoline and diesel;[36] and Column 6 shows net costs per ton of avoided CO_2.

Emission reduction estimates relative to the 2002 baseline vehicle range from 14-54 percent for the 14 minivan technology packages studied. According to this analysis, combinations of technologies already used in some production gasoline models can reduce CO_2 emissions by approximately 25 percent. Examples of these technologies include 5 and 6-speed automatic transmissions, variable valve lift and timing, and cylinder deactivation. Reductions beyond this level will require the introduction of more advanced technologies such as gasoline direct injection, 42-volt starter generators, and camless valve technology. Even greater CO_2 reductions can be achieved using hybrid-

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[36] As with all the vehicle classes analyzed, vehicle life is assumed to be 12 years and 150,000 miles. See Chapter 2 for more details.

electric designs. As with the large and small car cases, these advanced technologies are somewhat more costly than conventional gasoline technologies but fuel cost savings to the owner over the life of the vehicle usually far outweigh the additional cost. On a dollar per ton basis, the net cost of technologies required to produce CO_2 reductions up to 47 percent is negative, implying a net savings to the consumer.

As noted in Table 3-6, the emission reduction packages evaluated in this study include a wide range of individual technologies. Some of the most cost-effective packages include automated manual transmissions, cylinder deactivation, stoichiometric gasoline direct injection, turbocharging, and camless valve actuation. As with the large car category, turbocharging proves to be a very cost-effective technology because it enables the manufacturer to downsize the vehicle engine and decrease cylinder count while maintaining equal performance. Figure 3-3 depicts the relative benefits and costs of each of the evaluated technology packages. As this figure suggests, the technology packages span a broad range of CO_2-reduction potentials and costs.[37] For example, packages that achieve CO_2 reductions of 14-30 percent (i.e. emissions rates between 350 and 285 g/mi) encompass a net cost range from approximately negative $1,600 to negative $3. As with the vehicle classes discussed previously, the estimated CO_2 reduction supply curve for minivans developed in this study considers this full range of results, rather than only the least-cost solution, to allow for a more robust consideration of the benefits and costs of candidate CO_2-reduction technologies.

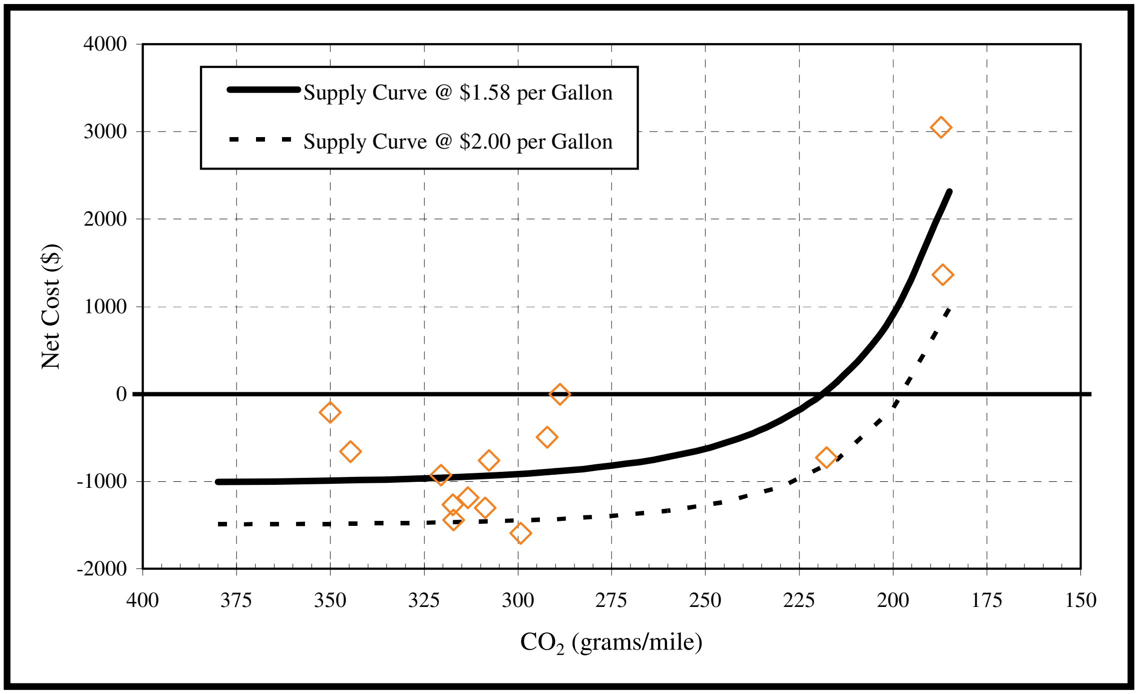
The solid line in Figure 3-3 represents the CO_2-reduction supply curve for the minivan class. As indicated, CO_2 reductions exceeding 29 percent (about 285 g/mi CO_2, relative to a 2002 baseline of 410 g/mi) are likely to be obtainable at net negative cost (i.e., while achieving lifetime savings). The figure also includes a second supply curve that reflects the results of a gasoline price sensitivity analysis in which the assumed prices of gasoline and diesel are increased from $1.58 to $2.00 per gallon. At the higher fuel price, all evaluated technology packages reflect negative net costs except for the advanced gasoline and diesel hybrids. It is also important to recognize that the costs used to develop Figure 3-3 are those estimated by Martec specifically for this study and adjusted to reflect estimated retail equivalents. If the generally lower cost estimates of the other studies included in Table 3-2 were considered, net costs would be shifted further to the negative. Nevertheless, even using Martec's cost estimates, the dashed line in Figure 3-3 suggests that at a gasoline price of $2 per gallon, vehicle owners can be expected to save $800-$1,500 over the life of the vehicle with the addition of technologies that reduce CO_2 emissions to approximately 220 g/mi (a 47 percent reduction from baseline 2002 emissions of approximately 410 g/mi). Assuming a gasoline price of $1.58, vehicle owners estimated to save $0-1,000 over the life of a vehicle for the same level of emission reduction.

[37] As stated in the discussion for the large car class, this study intentionally focused on a broad range of technology packages that provide for an equally broad range of CO_2-reduction potential and CO_2 reduction cost. See footnote 35.

Table 3-6: Minivan Results

(1) Technology Combinations	(2) CO_2 (g/mi)	(3) CO_2 Change (percent)	(4) Marginal Vehicle Cost ($)	(5) Net Cost ($)	(6) Net Cost ($ per ton CO_2)
Dual Cam Phasers, 6-Speed Automatic Transmission	350.0	14.3%	862	-212	-22
Discrete Variable Valve Lift, Coupled Cam Phasers, 5-Speed Automatic Transmission	344.6	15.6%	528	-659	-63
Stoichiometric Gasoline Direct Injection, Coupled Cam Phasers, Cylinder Deactivation, Automated Manual Transmission, Electric Power Steering, Improved Alternator	320.5	21.5%	759	-929	-64
Discrete Variable Valve Lift, Coupled Cam Phasers, Automated Manual Transmission, Electric Power Steering, Improved Alternator	317.4	22.3%	494	-1,266	-84
Coupled Cam Phasers, Automated Manual Transmission, Turbocharging, Electric Power Steering, Improved Alternator	317.1	22.3%	322	-1,440	-96
Diesel Homogeneous Charge Compression Ignition, Automated Manual Transmission, Electric Power Steering, Improved Alternator	313.3	23.3%	1,526	-1,186	-75
Cylinder Deactivation, Discrete Variable Valve Lift, Coupled Cam Phasers, Automated Manual Transmission, Electric Power Steering, Improved Alternator	308.8	24.4%	638	-1,302	-79
Continuous Variable Valve Lift, Coupled Cam Phasers, Automated Manual Transmission, Electric Power Steering, Improved Alternator	307.7	24.6%	1,219	-761	-46
Stoichiometric Gasoline Direct Injection, Dual Cam Phasers, Turbocharging, Automated Manual Transmission, Electric Power Steering, Improved Alternator	299.2	26.7%	559	-1,594	-88
Electrohydraulic Camless Valve Actuation, Stoichiometric Gasoline Direct Injection, Automated Manual Transmission, Electric Power Steering, Improved Alternator	292.2	28.4%	1,809	-493	-26
Stoichiometric Gasoline Direct Injection, Coupled Cam Phasers, Automated Manual Transmission, 42 Volt Integrated Starter/Generator, Cylinder Deactivation, Electric Power Steering, Electric Accessories	288.8	29.3%	2,374	-3	0
Motor Assist Gasoline Hybrid	217.8	46.7%	3,179	-726	-23
Fully Integrated Diesel Hybrid	187.2	54.2%	8,135	3,051	83
Fully Integrated Gasoline Hybrid	186.7	54.3%	5,944	1,366	37

Figure 3-3: Net Vehicle Costs for the Minivan Class Given Two Gasoline Price Scenarios



Small Truck Results

Table 3-7 presents the emission reduction and cost estimates for the 14 technology packages modeled for the small truck class.

Emission reduction estimates for this class range from 17-53 percent, relative to the 2002 baseline vehicle, for the 14 small truck technology packages evaluated. According to this analysis, combinations of technologies already used in some production gasoline models can reduce CO_2 emissions by approximately 28 percent. Examples of these technologies include 6-speed automatic transmissions, variable valve lift and timing, and cylinder deactivation. Reductions beyond this level will require the introduction of more advanced technologies such as gasoline direct injection, 42-volt starter generators, camless valve actuation, and diesel engine technology. For example, a technology package consisting of stoichiometric gasoline direct injection and camless vale actuation can provide a 32 percent CO_2 reduction for an incremental vehicle cost of about $1,500. Even greater CO_2 reductions can be achieved using hybrid-electric technology. As with the other categories of vehicles, fuel cost savings to the owner over the life of the vehicle generally outweigh the additional technology costs in all but the most aggressive technology packages. On a dollar per ton basis, the net cost of technologies producing CO_2 reductions up to 46 percent is negative, implying net cost savings to the consumer.

Table 3-7: Small Truck Results

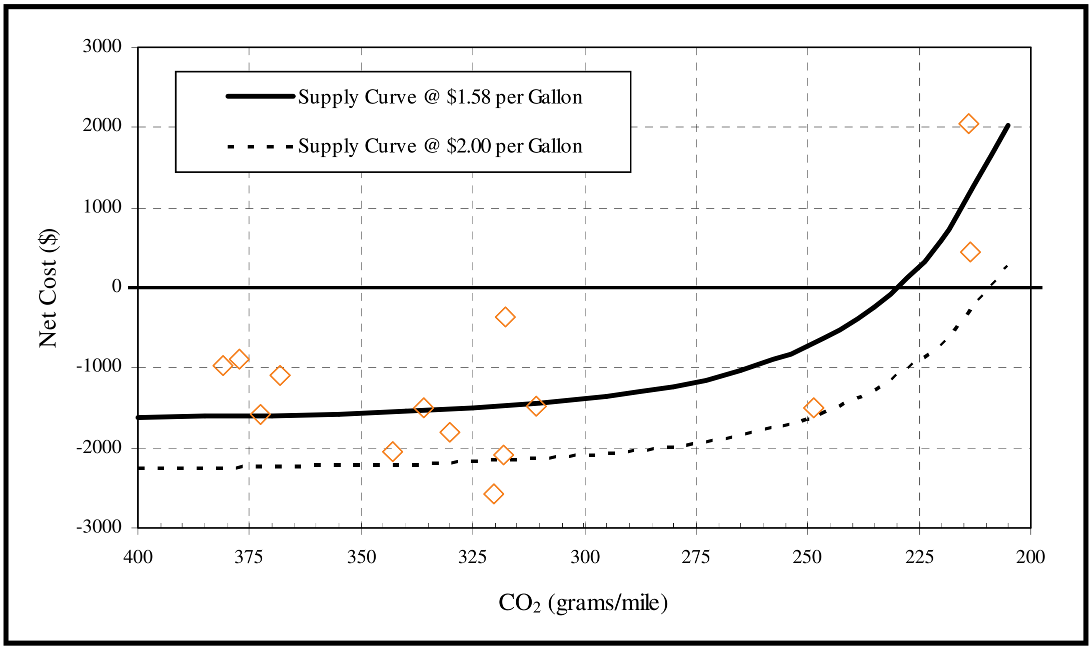
(1) Technology Combinations	(2) CO_2 (g/mi)	(3) CO_2 Change (percent)	(4) Marginal Vehicle Cost ($)	(5) Net Cost ($)	(6) Net Cost ($ per ton CO_2)
Dual Cam Phasers, 6-Speed Automatic Transmission	381.1	16.7%	479	-972	-77
Discrete Variable Valve Lift, Dual Cam Phasers, 6-Speed Automatic Transmission	377.4	17.5%	640	-902	-68
Dual Cam Phasers, 6-Speed Automatic Transmission, Turbocharging, Electric Power Steering, Improved Alternator	372.6	18.6%	73	-1,575	-112
Dual Cam Phasers, 6-Speed Automatic Transmission, Cylinder Deactivation	368.2	19.5%	634	-1,095	-74
Diesel Homogeneous Charge Compression Ignition, Automated Manual Transmission, Electric Power Steering, Improved Alternator	342.8	25.1%	1,156	-2,056	-108
Stoichiometric Gasoline Direct Injection, Dual Cam Phasers, Cylinder Deactivation, Automated Manual Transmission, Electric Power Steering, Improved Alternator	335.9	26.6%	906	-1,503	-75
Cylinder Deactivation, Discrete Variable Valve Lift, Coupled Cam Phasers, Automated Manual Transmission, Electric Power Steering, Improved Alternator	330.2	27.8%	750	-1,797	-85
Stoichiometric Gasoline Direct Injection, Dual Cam Phasers, Turbocharging, Automated Manual Transmission, Electric Power Steering, Improved Alternator	320.3	30.0%	157	-2,582	-114
Diesel High Speed Direct Injection, Automated Manual Transmission, Electric Power Steering, Improved Alternator	318.2	30.5%	1,585	-2,093	-91
Cylinder Deactivation, Discrete Variable Valve Lift, Coupled Cam Phasers, 6-Speed Automatic Transmission, 42 Volt Integrated Starter/Generator, Electric Power Steering, Electric Accessories	317.6	30.6%	2,451	-368	-16
Electrohydraulic Camless Valve Actuation, Stoichiometric Gasoline Direct Injection, Automated Manual Transmission, Electric Power Steering, Improved Alternator	310.9	32.1%	1,459	-1,487	-61
Motor Assist Gasoline Hybrid	248.6	45.7%	2,797	-1,496	-43
Fully Integrated Diesel Hybrid	214.0	53.2%	7,683	2,050	51
Fully Integrated Gasoline Hybrid	213.5	53.3%	5,492	439	11

As is evident from Table 3-7, the emission reduction packages evaluated in this study include a wide range of individual technologies. Some of the most cost-effective packages include stoichiometric gasoline direct injection, automated manual transmissions, turbocharging, camless valve actuation, and diesel technology. As noted early in this chapter, not all technology combinations considered for the large car vehicle class were evaluated for the small truck and other vehicle classes. Had these additional combinations been evaluated, comparable results would likely have been obtained for the small truck class. Finally, as with each of the other vehicle classes studied, this assessment also included options that are relatively expensive in an effort to provide a robust overview of the benefits and costs of a full range of candidate CO_2-reduction technologies.

Figure 3-4 depicts the relative benefits and costs of each of the evaluated technology packages. As this figure suggests, the technology packages span a broad range of CO_2 reduction potentials and costs. For example, packages that produce CO_2 reductions ranging from 17-32 percent (corresponding to CO_2 emission rates between 380 g/mi and 310 g/mi) encompass a net cost range from approximately negative $2,600 to negative $400. The solid line in Figure 3-4 presents the CO_2 reduction supply curve for the small truck class. As indicated, CO_2 reductions exceeding 45 percent are likely to be obtainable for a net negative cost. The figure also includes a second supply curve that reflects the results of a gasoline price sensitivity analysis in which the assumed prices of gasoline and diesel fuel are increased from $1.58 per gallon to $2.00 per gallon. At the higher fuel price, all evaluated technology packages reflect negative net costs with the exception of the advanced diesel hybrid. As can be seen from the dashed line ($2.00 per gallon gasoline), vehicle owners can be expected to save an average of $1,600-$2,200 over the life of a vehicle for CO_2 reductions to approximately 250 g/mi, which represent about a 46 percent reduction from 2002 emissions of about 460 g/mi. Significant savings can actually be expected for reductions as low as 215 g/mi CO_2, a reduction of nearly 54 percent from 2002 emissions. When a gasoline price of $1.58 are evaluated, vehicle owners can generally be expected to save $700-$1,700 over the life of a vehicle, except in the advanced hybrid cases. The introduction of CO_2 reducing technologies in the small truck category provides high net savings to consumers due to the relatively high baseline CO_2 emissions for this class, which results in greater fuel savings compared to the lower CO_2 classes evaluated in this study.

The solid line in Figure 3-4 represents the CO_2-reduction supply curve for the small truck class. As indicated, emission reductions exceeding 45 percent are likely to be obtainable for a net negative cost. As before, the figure includes a second supply curve that reflects a higher fuel price of $2.00 per gallon. At this price, all evaluated technology packages except the advanced diesel hybrid achieve negative net costs, with savings ranging from $1,600-$2,200 over the life of the vehicle for technologies that achieve a CO_2 emissions rate of 250 g/mi (about a 46 percent reduction from the 2002 baseline of 460 g/mi). Significant savings can actually be expected for technology packages that achieve emission rates as low as 215 g/mi, a reduction of nearly 54 percent from the 2002 baseline. Assuming a lower gasoline price of $1.58 per gallon, estimated net lifetime savings range from $700 to $1,700, except in the advanced hybrid cases. The introduction of CO_2-reducing technologies in the small truck category provides substantial net savings to consumers due to the relatively high baseline CO_2 emissions for this class. This results in proportionally higher fuel savings compared to vehicle classes that have lower baseline CO_2 emissions.

Figure 3-4: Net Vehicle Costs for the Small Truck Class Given Two Gasoline Price Scenarios



Large Truck Results

Table 3-8 presents the emission reduction and cost estimates for the 14 technology packages investigated for the large truck class.

Emission reduction estimates range from 14-55 percent, relative to the 2002 baseline vehicle, for the 15 large truck technology packages modeled. According to this analysis, combinations of technologies already used in some production gasoline models can reduce CO_2 emissions by approximately 24 percent. Examples of these technologies include 6-speed automatic transmissions, variable valve lift and timing, and cylinder deactivation. Reductions beyond this level will require the introduction of more advanced technologies such as gasoline direct injection, camless valve actuation, and diesel technology, which can provide up to a 30 percent CO_2 reduction. Even greater CO_2 reductions can be achieved using hybrid-electric designs. On a dollar per ton basis, the net cost of technologies producing CO_2 reductions of up to 46 percent is negative, resulting in overall savings over the life of the vehicle.

As noted in Table 3-8, the emission reduction packages evaluated in this study include a wide range of individual technologies. Some of the most cost-effective packages include automated manual transmissions, cylinder deactivation, and stoichiometric gasoline direct injection. In the large truck class, cylinder deactivation was evaluated as a more viable technology rather than turbocharging and downsizing in order to ensure adequate durability for heavily loaded engines operating on work truck type duty cycles (high-load operations and payload and trailer towing).

Table 3-8: Large Truck Results

(1) Technology Combinations	(2) CO_2 (g/mi)	(3) CO_2 Change (percent)	(4) Marginal Vehicle Cost ($)	(5) Net Cost ($)	(6) Net Cost ($ per ton CO_2)
Coupled Cam Phasers, 6-Speed Automatic Transmission	452.5	13.7%	339	-1,037	-87
Discrete Variable Valve Lift, Coupled Cam Phasers, 6-Speed Automatic Transmission	444.2	15.3%	549	-981	-74
Coupled Cam Phasers, Cylinder Deactivation, 6-Speed Automatic Transmission	434.8	17.1%	543	-1,197	-81
Dual Cam Phasers, Cylinder Deactivation, 6-Speed Automatic Transmission	432.5	17.6%	1,120	-682	-45
Cylinder Deactivation, Discrete Variable Valve Lift, Coupled Cam Phasers, 6-Speed Automatic Transmission, Electrohydraulic Power Steering, Improved Alternator	419.7	20.0%	843	-1,228	-71
Coupled Cam Phasers, Cylinder Deactivation, Stoichiometric Gasoline Direct Injection, Automated Manual Transmission, Electrohydraulic Power Steering, Improved Alternator	418.3	20.3%	890	-1,207	-69
Lean Burn Gasoline Direct Injection, Automated Manual Transmission, Electrohydraulic Power Steering, Improved Alternator	400.5	23.6%	1,926	-528	-26
Cylinder Deactivation, Discrete Variable Valve Lift, Coupled Cam Phasers, Automated Manual Transmission, Electrohydraulic Power Steering, Improved Alternator	398.0	24.1%	731	-1,794	-86
Electrohydraulic Camless Valve Actuation, Stoichiometric Gasoline Direct Injection, Automated Manual Transmission, Electrohydraulic Power Steering, Improved Alternator	383.2	27.0%	2,171	-666	-28
Cylinder Deactivation, Discrete Variable Valve Lift, Coupled Cam Phasers, 6-Speed Automatic Transmission, 42 Volt Integrated Starter/Generator, Electric Power Steering, Electric Accessories	379.6	27.6%	2,430	-499	-21
Diesel Homogeneous Charge Compression Ignition, Automated Manual Transmission, 42 Volt Integrated Starter/Generator, Electric Power Steering, Electric Accessories	374.8	28.6%	3,535	-515	-21
Lean Burn Gasoline Direct Injection, Automated Manual Transmission, 42 Volt Integrated Starter/Generator, Electric Power Steering, Electric Accessories	367.1	30.0%	3,494	326	13
Motor Assist Gasoline Hybrid	285.9	45.5%	3,641	-1,312	-33
Fully Integrated Gasoline Hybrid	244.9	53.3%	7,540	1,709	37
Fully Integrated Diesel Hybrid	238.7	54.5%	10,592	3,978	84

The large truck category is the only vehicle class with an eight-cylinder base engine. Because of this, technology costs in the large truck class are in some cases higher than in the other vehicle classes due to additional hardware requirements. For example, eight lost motion devices are required for variable valve lift technology rather than six for other vehicle classes due to the additional cylinders. Despite these higher costs, fuel savings more than overcome incremental technology costs for nearly all the large truck technology packages evaluated.

Figure 3-5 graphically depicts the relative benefits and costs of each of the evaluated technology packages. As this figure suggests, the technology packages span a broad range of CO_2 reduction potential and costs.[38] For example, packages providing CO_2 reduction from 14 to 30 percent (emissions between 450 and 370 g/mi CO_2) encompass a net cost range from approximately negative $1,800 to positive $300. The estimated CO_2 reduction supply curve for this study considers this full range of results rather than only the least cost solutions. As previously noted, this approach is intended to allow for a more robust consideration of the benefits and costs of candidate CO_2 reduction technology.

The solid line in Figure 3-5 presents the CO_2 reduction supply curve for the large truck class. As indicated, CO_2 reductions of about 45 percent (about 285 g/mi CO_2, relative to about 525 g/mi for a 2002 vehicle) are likely to be obtainable for a net negative cost (e.g., a lifetime savings). The figure also includes a second supply curve that reflects the results of a gasoline price sensitivity analysis in which the assumed prices of gasoline and diesel fuel are increased from $1.58 per gallon to $2.00 per gallon. At the higher fuel price, all evaluated technology packages reflect negative net costs except the advanced gasoline and diesel hybrids. As can be seen from the dashed line ($2.00 per gallon gasoline), vehicle owners can be expected to save an average of about $900-$1,700 over the life of a vehicle for a range of CO_2 reductions up to about 45 percent. When gasoline prices of $1.58 are evaluated, vehicle owners can be expected to save an average of $0-$1,000 over the life of a vehicle for this same level of CO_2 reductions.

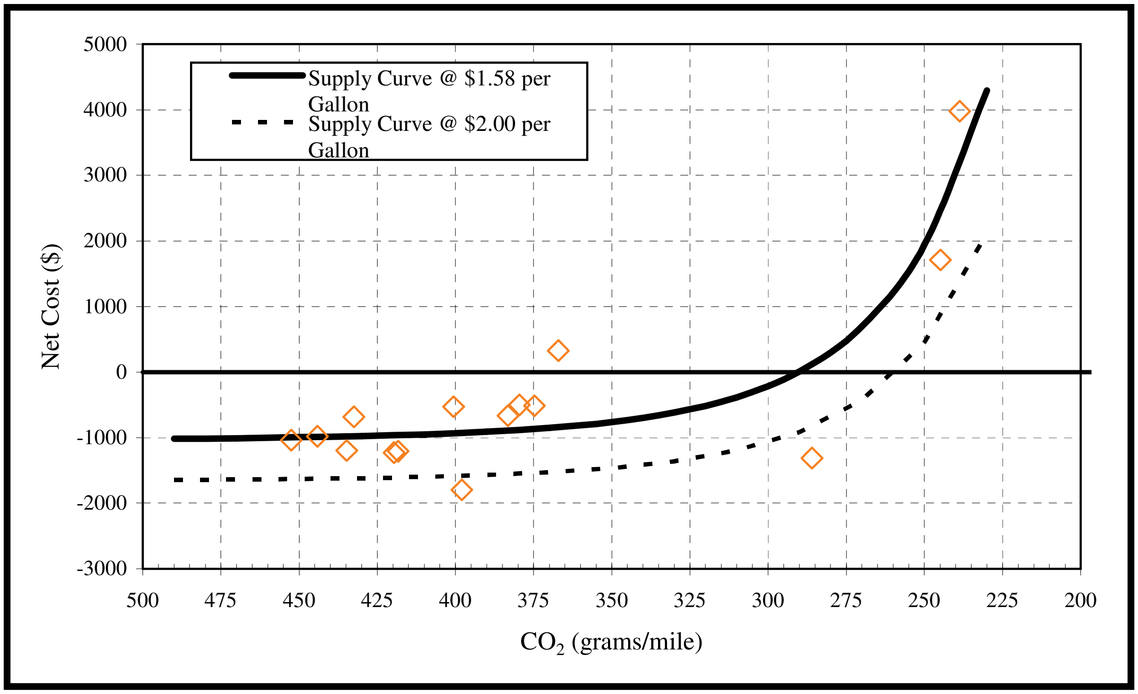
Figure 3-5 depicts the relative benefits and costs of each of the technology packages considered for large trucks. As with the other vehicle classes, these packages span a broad range of CO_2 reduction potentials and costs. For example, packages that provide CO_2 reductions of 14-30 percent (corresponding to CO_2 emission rates between 450 and 370 g/mi) encompass a net cost range from approximately negative $1,800 to positive $300.

The solid line in Figure 3-5 presents the CO_2-reduction supply curve for the large truck class. As indicated, CO_2 reductions of about 45 percent (corresponding to an emissions rate of about 285 g/mi relative to a 525 g/mi baseline for a 2002 vehicle) are likely to be obtainable at net negative cost (i.e., lifetime savings). The figure indicates

[38] As stated in the discussion for the large car class, this study intentionally focused on a broad range of technology packages that provide for an equally broad range of CO_2 reduction potential and CO_2 reduction cost. Thus, the study has not attempted to consider only the least cost solutions, but rather a broader range of solutions that might better reflect the cost of CO_2 reduction across the entire class of vehicles. While least cost solutions might be appropriate for some segments of the class, other segments might require a somewhat more expensive solution to maintain a critical market distinction.

that at the higher fuel price of \$2.00 per gallon, all evaluated technology packages achieve negative net costs except the advanced gasoline and diesel hybrids. Specifically, vehicle owners can be expected to save an average of about \$900-\$1,700 over the life of a vehicle for a range of CO_2 reductions up to about 45 percent. At the lower fuel price of \$1.58 per gallon, vehicle owners can be expected to save an average of \$0-\$1,000 over the life of a vehicle for this same level of CO_2 reductions.

Figure 3-5: Net Vehicle Large Truck Costs Given Two Gasoline Price Scenarios Methane and N_2O Analysis



Methane and Nitrous Oxide Analysis

Table 3-9 presents estimates for motor vehicle methane and N_2O emissions, produced according to the methods outlined in Chapter 2 and Appendix E. As indicated, the GHG impacts of methane and N_2O are estimated to be relatively modest compared to CO_2 emissions, which generally range from about 300-525 g/mi in 2002 and approach 150-240 g/mi under the most aggressive CO_2 reduction scenarios in 2009-2015. Given these ranges, methane emissions are generally estimated to represent from 0.04-0.08 percent of 2002 CO_2-equivalent emissions and no more than 0.1 percent of 2009-2015 CO_2-equivalent emissions under even the most aggressive CO_2 reduction scenarios. N_2O emissions are a bit more significant, comprising from 1-2 percent of 2002 CO_2-equivalent emissions and as much as 3 percent of 2009-2015 CO_2-equivalent emissions.

Estimated methane and N_2O impacts are not included in the overall CO_2 impact estimates presented in Tables 3-4 through 3-8, but are provided here to allow for a full accounting of all vehicle GHG emissions. To estimate total GHG emissions from a particular vehicle class and technology combination, the CO_2 emission estimates from

Tables 3-4 through 3-8 would be added to the CO_2-equivalent emission estimates for methane and N_2O from Table 3-9.

Table 3-9: Methane and N_2O Emissions

Basic Technology Configuration	Methane		Nitrous Oxide	
	2002	2009-2015	2002	2009-2015
Grams per Mile - Expressed as Direct Methane or Nitrous Oxide				
Stoichiometric	0.010	0.008	0.021	0.016
Lean Burn	0.005	0.005	0.016	0.016
Grams per Mile - Expressed as CO_2-Equivalent				
Stoichiometric	0.23	0.18	6.1	4.9
Lean Burn	0.12	0.12	4.9	4.9

3.3. Conclusions

The results of this analysis suggest that existing and emerging automotive technologies can achieve substantial and cost-effective reductions in motor vehicle GHG emissions in the 2009 to 2015 timeframe. Specifically, GHG emissions from light-duty vehicles can be reduced from 12-54 percent in this timeframe. Assuming a gasoline price of $1.58 per gallon, this study found that—for most technology packages—vehicle owners will save at least $500 over the life of the vehicle. At a higher fuel price of $2.00 per gallon, vehicle owners will save between $300 and $2,200 over the life of the vehicle for a range of CO_2 reductions up to about 45 percent.

Appendix A: Technology Descriptions

Appendix A: Technology Descriptions

A.1. Cam Phasing

Also known as variable valve timing, cam phasing indicates an ability to vary the point during the combustion cycle at which a valve is opened and closed. Most spark ignition engines currently use fixed valve timing, where the valve timing does not change with the speed or load of an engine. This results in higher pumping losses than could be achieved with optimum valve control. Variable valve timing offers the opportunity to implement speed and load-dependent (i.e., variable) operating conditions that can reduce pumping losses while enhancing both low-speed torque and high-speed horsepower.

A.2. Variable Valve Lift

Valve lift is a measure of the height and duration of the valve opening. Most spark gasoline engines use fixed valve lift, where the valve lift does not change with the speed and load of an engine. Variable lift allows the period of valve opening to vary which reduces pumping losses, reduces valve train frictional loss, increases compression ratio, and reduces idle speed—all of which reduce CO_2 emissions.

A.3. Camless Valve Actuation

Camless valve actuation expands upon the concept of variable valve timing and lift, described above, by completely eliminating the camshaft and mechanical valve actuation mechanism from the cylinder head. In place of the camshaft mechanism, valve motion is actuated and controlled through either electrical energy or hydraulic energy, and this can occur over a wide range of engine operating conditions. This yields greater CO_2 reductions than variable valve lift/timing systems.

A.4. Turbocharging

Internal combustion engines reject 25 to 50 percent of energy into the exhaust. A turbocharged engine uses a turbine in the exhaust stream to drive a compressor in the intake manifold, which compresses incoming air to the engine. The higher pressure air in the intake manifold forces more air into the engine than would otherwise be the case, and the resulting benefit is an increase in engine power. While the technology doesn't reduce CO_2 emissions directly, the fact that the engine produces greater power allows engines to be downsized without sacrificing performance, and this downsizing can produce significant CO_2 reductions.

A.5. Cylinder Deactivation

Cylinder deactivation technology allows engines to operate on half their cylinders during certain operating modes. Generally, such systems “shut down” cylinders during light load operation so that the engine operates with an efficiency similar to that of a lower-displacement engine. From an engineering standpoint, the major CO_2 reductions accrue due to a reduction in pumping losses associated with halving the number of cylinders in operation. The more frequently the deactivation mode occurs, the greater the CO_2 reduction impacts. Therefore, in some cases, the base engine may be upsized to allow more frequent operation in deactivation mode, which results in both reduced CO_2 and greater maximum power.

A.6. Variable Compression Ratio

Engine efficiency increases with cylinder compression ratio. The greater the compression, the more work performed for a given air-fuel mixture. In standard technology engines, the compression ratio is fixed across all operating conditions based on cylinder geometry. However, the tendency of engines to experience knock varies with operating conditions. For example, at light loads, higher compression ratios can be tolerated without knock. However, since the geometry of a standard engine cannot be varied it is not possible to optimize compression ratios for specific operating conditions. New engine designs can mechanically vary cylinder geometry. This allows for engines that operate at a high-compression ratio under part-load conditions and at a lower compression ratio under high-load conditions. CO_2 reductions are achieved through the use of a smaller engine to achieve identical performance.

A.7. Gasoline Direct Injection

Gasoline direct injection (GDI) technology facilitates lean-burn engine operation. Lean-burn engines mix more air with the fuel when full power is not needed, resulting in lower CO_2 emissions. Charge "shaping" possible with lean-burn engines facilitates ignition of the air-fuel mixture at very lean overall air-fuel ratios. Under lean-burn conditions, highly effective lean NO_x aftertreatment will be required for GDI technology to achieve Tier 2 emission standards, which adds significantly to technology costs. However, even under stoichiometric conditions, GDI technology can provide significant CO_2 reductions due to its ability to tolerate increased compression ratio and increased exhaust gas recirculation (EGR). The advanced air and fuel control features of GDI engines allow them to be operated at either stoichiometric (high-load conditions) or lean-burn (light-load conditions) as required.

A.8. Homogeneous Charge Compression Ignition (HCCI)

The design goal of HCCI combustion is the incorporation of the best features of gasoline/spark-ignition (SI) and diesel/compression-ignition (CI) engines. Like an SI engine, the intake charge, or fuel/air mixture, is well-mixed (hence the label "homogeneous charge"), and like the CI engine the intake charge is compression-ignited (no spark plug) at high compression ratios, with minimal throttling losses. This leads to high operating efficiencies, low CO_2 emissions, and low NOx and PM emissions. HCCI is not yet feasible across the full engine operating range, so it is generally employed as a partial mode system, where HCCI is utilized under light load conditions and more conventional combustion modes are used at higher speeds and loads. For this study, both gasoline and diesel HCCI systems were evaluated. The gasoline HCCI system is based on GDI technology, and the spark ignition features of the GDI engine are retained for operation in non-HCCI modes. The gasoline HCCI system evaluated was the AVL CSI (Compression and Spark Ignition) system, a very low NO_x and CO_2 combustion system that can operate with a conventional 3-way catalyst. The diesel version of the HCCI system is denoted as Diesel Advanced Multi-Mode in this study and is essentially a light load HCCI system that shifts to conventional high-speed direct injection (HSDI) diesel operation at high loads and speeds. Advanced common rail injection systems capable of precisely tailored multiple injections per cycle facilitate the HCCI operations.

A.9. High-Speed Direct Injection Diesel (HSDI)

Heavy-duty diesels have historically been of direct injection (DI) design, where fuel is directly injected into the engine combustion chamber. Conversely, light-duty versions – primarily used in Europe and Asia – have historically avoided the vibration and harshness issues associated with DI designs by using indirect-injection (IDI) designs, whereby fuel is injected into a pre-chamber and the resulting air-fuel mixture is subsequently introduced into the main combustion chamber. However, with the advent of sophisticated, electronically-controlled fuel injection systems, it is possible to experience the quiet, smooth operation of the IDI, with the low-CO_2 emissions characteristic of DI engines. However, a primary impediment facing HSDI technology in the U.S. marketplace is stringent NO_x and PM emission regulations, which will necessitate the use of highly effective lean aftertreatment systems.

A.10. 5 and 6 Speed Automatic Transmissions (Increased Step Gear Ratio Transmissions)

In both automatic and manual transmissions, increasing the number of gears can provide a wider spread between the lowest (first gear) and highest gear ratios. This allows the engine to operate closer to its optimum efficiency at a wider variety of speeds which results in a corresponding decrease in CO_2 emissions. Five and six speed automatic transmissions are now available, both of which provide benefits relative to the more traditional four-speed transmission.

A.11. Automated Manual Transmissions

An automated manual transmission is similar in design and performance to a manual transmission, except that shifting and clutch control is performed automatically outside the control of the driver. These functions instead occur by means of a hydraulic system or an electric motor, in conjunction with appropriate control electronics. Lower CO_2 emissions result from the elimination of automatic transmission torque converter losses and the programming of optimum shift points.

A.12. Continuously Variable Transmissions

Current transmissions feature a discrete number of gear ratios (generally four to six) that determine the relationship between engine speed and vehicle speed. This results in some compromise in matching engine speed and load-to-vehicle requirements. A continuously variable transmission (CVT) offers an infinite range of gear ratios between fixed limits, which allows for the optimization of engine operating conditions and maximum power transmission efficiency.

A.13. 42 Volt Systems

Forty-two volt systems enable a number of CO_2 reducing features, including engine off at idle, launch assist, regenerative braking, electrical accessory drives, and electric power steering. While any one of these (except launch assist) can be accomplished using current 12-volt automotive systems, the unused power available on current systems is a major limitation. In contrast to the 3 kW available with current 12-volt systems, 42-volt systems can provide up to 12 kW maximum power and, thereby, accommodate significant power-related upgrades. In 42-volt systems, the existing vehicle starter and alternator are replaced by a combined starter/alternator. The simplest implementation is a belt-driven starter/alternator, but such systems are limited in their ability to provide launch assist or regenerative braking benefits. A more complex system in which the starter/alternator is sandwiched between the engine and transmission allows substantial launch assist and regenerative braking, as well as other benefits such as a reduction in required torque converter size and a reduction in engine torque pulsation.

A.14. Hybrid Electric Vehicles (HEVs)

Hybridization involves the interaction, in varying degrees depending on the design, of a conventional gasoline or diesel-powered powerplant, in conjunction with an electric motor. Parallel hybrids use the conventional engine coupled directly to the vehicle's drivetrain as the prime motive power with varying degrees of electric motor assist. Series hybrids also employ a conventional engine, but it is physically de-coupled from the drivetrain, making the electric motor the only motive source. The conventional engine provides power to operate a generator providing power to a battery pack, which in turn provides electric power to operate the electric motor. Reduced CO_2 emissions are achieved through a number of mechanisms, including utilization of smaller engines that operate in a more efficient power band, energy recovery through regenerative braking, engine shutdown at what would normally be idling conditions, and other strategies.

A.15. 12-Volt Accessory Improvements

Engine-driven accessories account for eight to ten percent of the CO_2 emitted over a typical driving cycle. Such accessories include the alternator, oil pump, water pump, and power steering pump. A typical vehicle alternator has an efficiency of around 60 percent, as compared with advanced designs that can provide 75-80 percent efficiency. Similar advances are possible with improved oil and water pump designs. Power steering pumps are somewhat different in that they operate continuously, but are needed intermittently. Electrical (instead of hydraulic) systems can significantly reduce CO_2 emissions by eliminating this continuous load.

A.16. Lubricating Oil

Lubricating oil serves several functions within an engine, including: friction reduction, engine cooling, limiting wear on the moving parts of the engine, and protecting against corrosion. It is primarily the effect of lubricating oil on engine friction that impacts CO_2 emissions. New energy-conserving motor oils reduce engine frictional forces.

A.17. Drag Reduction

Reductions in vehicle aerodynamic drag have the effect of reducing the load on a vehicle engine and thereby reducing CO_2 emissions. Aerodynamic drag is a resistance force that acts on the surface of a moving vehicle. The force varies with wind intensity, direction, vehicle frontal area, and body shape. Apart from basic vehicle shape changes, drag reduction is generally achieved by minimizing air friction over vehicle surfaces. For example, skirts, air dams, and underbody covers can all reduce aerodynamic friction. The implementation of drag reduction technology generally leads a modest increase in the weight of the vehicle, but the CO_2 emission reductions due to the reduced drag outweigh the penalties of the increased weight.

A.18. Weight Reduction

Vehicle weight is a principal determinant of vehicle CO_2 emissions. Lower vehicle weight reduces the forces required to accelerate the vehicle and maintain steady speeds, which in turn reduces CO_2 emissions. Generally, weight can be reduced through the replacement of conventional steel with lighter-weight alternatives, improved packaging, or downsizing. Modern lightweight materials include high-strength low-alloy (HSLA) steel, aluminum, magnesium alloys, and plastics. Downsizing also reduces vehicle weight since it takes less material to make a smaller car.

A.19. Rolling Resistance Reduction

Rolling resistance is a measure of the force required to move the tires of a vehicle forward. When multiplied by the radius of the tire, this force gives the resistive torque that must be overcome by the engine when the vehicle is in motion. The rolling resistance of a tire can be reduced through improved tread and shoulder designs and the use of improved materials for tire belt and traction surfaces.

A.20. Aggressive Shift Logic

Aggressive shift logic changes the points at which shifting occurs to reduce CO_2 emissions. Moving transmission upshift points to lower speeds offers the potential for reduced CO_2 emissions. As upshift speeds are lowered, downshift speeds must be altered to avoid excessively busy shifting behavior. However, if the downshift speeds are reduced too much, then the driveability of the vehicle can suffer because it won't respond to driver demands for acceleration.

A.21. Early Torque Converter Lock-up

The torque converter, which prevents stalling on automatic transmission vehicles at rest, is one of the largest sources of inefficiency in the vehicle. The advent of torque converter lock-up clutches was a major contributor to reducing CO_2 emissions. However, the full potential of this technology is not used because the rigid connection to the engine transmits vibrations at low engine speeds to the interior of the vehicle.

A.22. Alternative Fuels

Alternative fuels can be used alone or in combination with many of the technologies described above to reduce GHGs. However, large-volume sales of alternative fuel vehicles are affected by refueling infrastructure issues that introduce levels of uncertainty beyond those associated with gasoline and diesel vehicle sales. Therefore, while alternative fuel vehicles represent a viable and efficient means to reducing motor vehicle GHG emissions, they were not examined in this study.

Nevertheless, the use of alternative fuels should be considered alongside the technologies identified in this study in formulating a cost-effective GHG reduction strategy.

Appendix B: AVL Simulation Modeling Description

Appendix B: AVL Simulation Modeling Description

B.1. Vehicle Simulation

The vehicle simulation software AVL CRUISE was used to evaluate Greenhouse Gas (GHG) emissions considering combinations of engine and driveline technologies. CRUISE is used to simulate CO2, criteria exhaust emissions, fuel consumption, and vehicle performance. Emissions were simulated over three standard test cycles: FTP75, HWFET, and US06. For this project, vehicle performance includes full load acceleration from rest to 60 MPH, from 50 MPH to 70 MPH in top gear (representing a passing situation), full load climbing performance at curb and gross vehicle weights and the maximum velocity of the vehicle. An additional climbing task, with a 5000lb trailer, was also performed for the truck models.

After the baseline vehicles had been selected (as described in chapter 2 of this report), data was collected and the models developed. The 2002 model year (MY2002) vehicles are described in more detail in Section B.2 of this appendix. Section B.3 presents the engine technology options. Sections B.4 through B.7 describe the modifications required to convert the MY2002 model from a 4 speed automatic transmission (4AT) to more advanced transmissions such as a 6 speed automatic transmission (6AT). Section B.8 illustrates the approach used to model Hybrid drive trains and Section B.9 covers other vehicle technologies that were considered, such as the effects of additional mass, changes in drag coefficients, air conditioning, and the electrification of auxiliaries. Section B.10 presents the simulation results from all the models developed by AVL for the project.

B.2. MY2002 Baseline Models

A review of the vehicles in the current consumer vehicle fleet resulted in a description of base vehicles that were then modeled in CRUISE. These CRUISE models were calibrated to provide similar 0-60 MPH times to published data and fuel economy on the emissions test cycles that matched EPA test car data. These configurations all share similar technology, including MPFI internal combustion engines and 4 speed automatic transmissions.

Figure B-1 presents the baseline model for a front wheel drive (FWD) vehicle. This configuration represents the small car (SC), large car (LC), and minivan (MV) models. Figure B-2 shows a four-wheel drive (4WD) model, which is typical of the small and large truck vehicles (ST and LT respectively). The primary difference between the models is the addition of a single ratio transmission and differential representing the rear axle and a clutch between the front and rear axles. A clutch was included to disengage the power transmission to the front axle. The small and large trucks were determined to be split nearly 50% between 2WD and 4WD. Since many 4WD vehicles can also be run in a 2WD mode, it was decided to include the components for the 4WD but to disengage the front axle in order to capture the losses associated with the non-driven axle. The rest of this section will detail each of the components shown in Figures B-1 and B-2.

Figure B-1: Layout of the Front Wheel Drive Vehicles (Small Car shown)

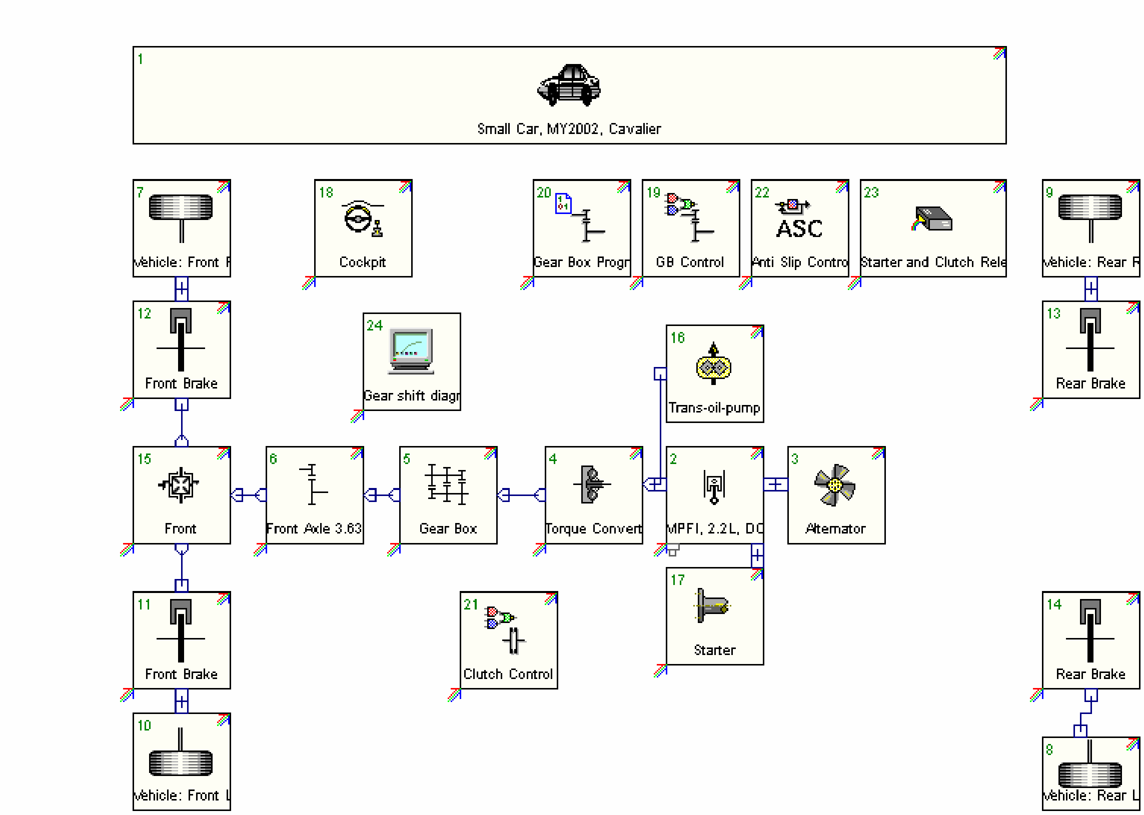
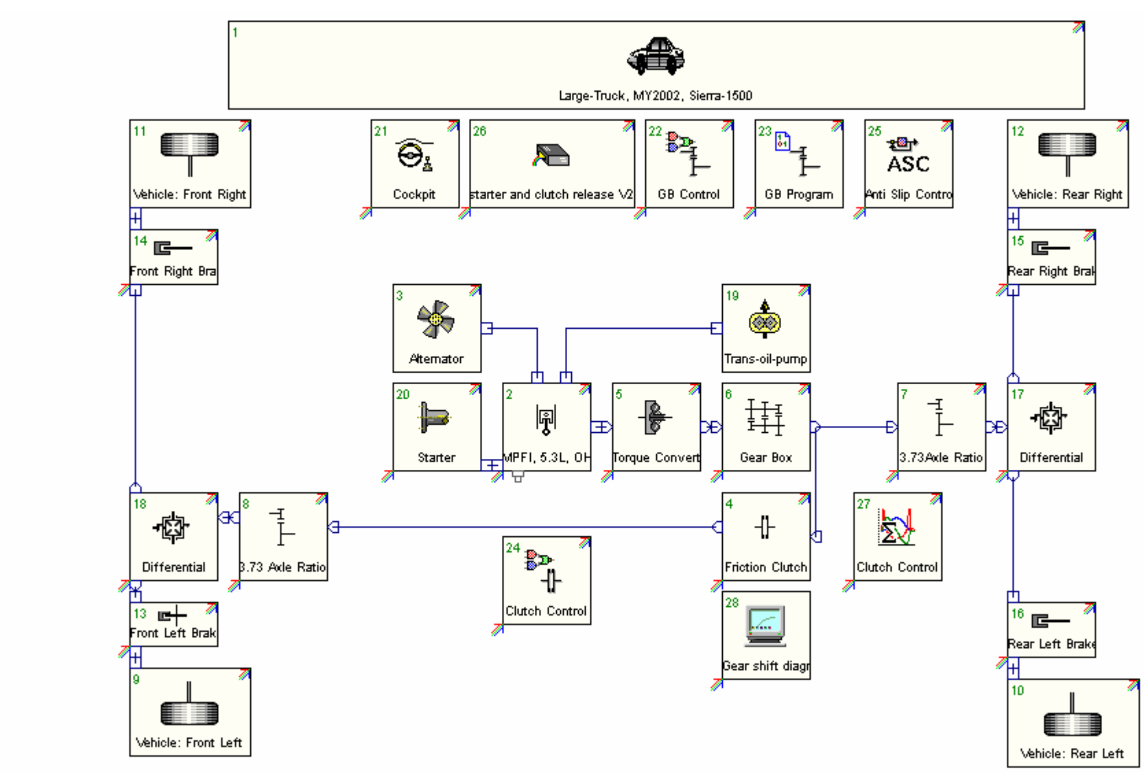
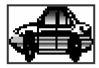


Figure B-2: Layout of the 4 Wheel Drive Vehicles (Large Truck shown)



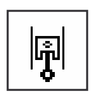
B.2.1. Vehicle Component 

The vehicle component contains the general data of the vehicle such as nominal dimensions and weights. For this project, coefficients defining the resistance of the vehicle were obtained from data published by the EPA. Additional details, such as the wheelbase, were taken from OEM data for the particular vehicle. The more important data entered in the vehicle models are summarized in Table B-1.

Table B-1: Vehicle Component data for all vehicle classes

Parameter	**Units**	**Small Car**	**Large Car**	**Minivan**	**Small Truck**	**Large Truck**
Wheelbase	mm	2644	2756	3030	3096	3645
Curb weight	lbm	2676	3336	4107	3540	4919
Equivalent Test Weight	lbm	3000	3625	4500	4250*	5500*
Gross Weight	lbm	3176	3836	4700	5100	6400
EPA coefficient A	lbf	27.9	30.19	36.16	47.889	29.8
EPA coefficient B	lbf/ mph	0.3677	0.6723	0.8909	0.32911	1.9928
EPA coefficient C	lbf/ mph^2	0.01743	0.01323	01812	0.034627	0.02435

* ETW chosen to coincide with EPA fuel economy test data

B.2.2. Engine Component 

The primary source of power for the vehicle is the internal combustion engine. The engine is modeled by a structure of characteristic curves and maps. The full load and motoring curves define the high and low torque limits of the engine. During each calculation, the engine speed and torque are used to interpolate the emissions and fuel consumption from steady state maps entered in the component. A temperature model is included to consider the influence of the temperature on the emissions and fuel consumption while the engine is cold.

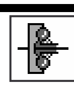
The thermal model was used to simulate the warm-up for the FTP75 cycle, as well as the temperature loss during the soak (engine-off) period. Typical times to reach the engine operating temperature were between 180-300 seconds. For the Highway and US06 cycles, a hot start was used with transient engine temperature behavior allowed.

Typical engine parameters for the baseline vehicles are presented in Table B-2. Full load curves from AVL data were adapted to meet the torque and power specifications for the baseline vehicles. For Task 1 the engine displacement was unchanged for the varying engine technologies, except for the turbocharged and diesel engine options. For these cases, the engine displacement was adjusted in order to match 2002 performance levels. In Task 2, the engine was sized to meet the projected 2009 performance levels for all simulations.

Table B-2: Engine Parameters

Parameter	Units	Small Car	Large Car	Minivan	Small Truck	Large Truck
Type	-	Gasoline	Gasoline	Gasoline	Gasoline	Gasoline
Turbo	-	No	No	No	No	No
Displacement	L	2.2	3.0	3.3	3.4	5.3
# of cylinders	-	4	6	6	6	8
Max. speed	RPM	6500	6200	5600	5800	6000
Idle speed	RPM	850	650	650	650	550
Max torque	Nm	202.9	271.0	284.6	298.1	440
Max power	kW	104.4	149.1	134.2	141.7	213

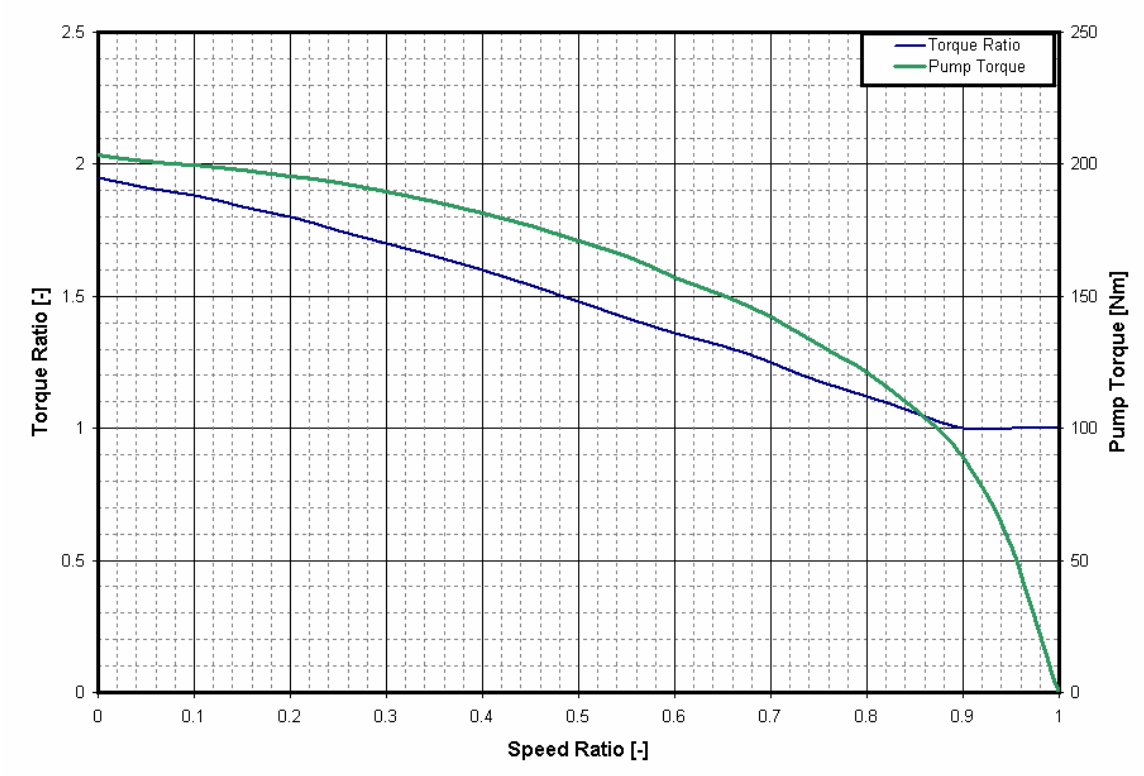
B.2.3. Torque Converter



For most light duty vehicles in the U.S., the torque converter is the device used for decoupling the engine from the drive wheels when the vehicle is at rest and for launching the vehicle. Torque converters employ the force created by a moving fluid to transmit engine torque to the gearbox. The torque converter also multiplies torque when there exists a positive speed difference from the engine side to the transmission side. An impeller (pump) converts the mechanical energy from the power source into fluid energy. The fluid energy then is converted back to mechanical energy as a result of fluid pressure on the turbine blades.

Characteristic curves available from published papers were used when possible. In other cases, curves were estimated based on a combination of published torque ratios at stall, K-factors at stall, capacity factors at stall, and characteristic curves available in "Design Practices, Passenger Car Automatic Transmissions 3rd Edition" pages 75-102 published by SAE. Other sources of information included SAE paper 980821, which contained a chart relating the K-factor range versus torque converter diameter. The Hydramatic website also provided information regarding the torque converter diameter in each of GM's applications. In those cases where estimation of the performance was necessary, the GM vehicle in that class was used to provide the size of the converter and as a result a range of nominal K-factors at stall. A typical torque converter steady state characteristic is shown in Figure B-3.

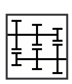
Figure B-3: Typical characteristics for torque converter in steady state operation



The torque converters were also outfitted with a lock-up clutch. These lock-up clutches are used to decrease CO2 emissions by making a rigid connection between the incoming and the outgoing sides of the torque converter when the slip is low. The maximum torque of the lock-up clutch was set to a level that was greater than the engine torque to guarantee that no slip would occur when the lock-up clutch was closed (torque transmitted through the clutch).

B.2.4. Torque Converter Lock-up Control Strategy

The clutch control map is used for lock-up clutches of torque converters. The Clutch Control element controls the opening and closing of this lock-up clutch based on the engine speed, current gear, and load signal. For the 4AT, lock up was only allowed in 3^{rd} and 4^{th} gears.

B.2.5. Gear Box 

The Gear Box component contains a model for a gear box with different gear steps. As many gears as required can be defined. For each gear the transmission ratio, the mass moments of inertia, and efficiency were defined. The gear box component can be used for a manual or automatic gear box. When used as an automatic gear box, the gear shifting process is controlled by the Gear Box Control or Gear Box Program. The CRUISE virtual driver will handle this task when used as a manual gear box.

Relative efficiencies appropriate to the architecture of the gear box and considering the number of gear sets in mesh and transmitting torque for the particular ratio were established for each gear. Absolute gear efficiencies (as well as final drive efficiencies) were then set to match published performance values for the baseline vehicles. Table B-3 contains the ratios and the efficiencies for each of the gears in the baseline transmission.

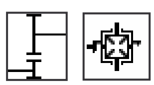
Table B-3: Gear Ratios and Efficiencies for each of the vehicle classes

	Small Car		Large Car		Minivan		Small Truck		Large Truck	
	Ratio	η	Ratio	η	Ratio	η	Ratio	η	Ratio	η
Gear 1	2.96	0.94	2.77	0.945	2.84	0.945	2.804	0.95	3.06	0.95
Gear 2	1.63	0.955	1.54	0.96	1.57	0.96	1.531	0.965	1.625	0.965
Gear 3	1.0	0.97	1.0	0.975	1.0	0.975	1.0	0.98	1.0	0.98
Gear 4	0.68	0.955	0.69	0.96	0.69	0.96	0.705	0.965	0.7	0.965

B.2.6. Gear Shift Controls for AT and AMT Transmissions

The shifting of the gear box is controlled by the Gear Box Control or Gear Box Program components. The Gear Box Control is used during the steady state calculations for the maximum acceleration in each gear and in the climbing performance tasks. During the elasticity (passing from 50 MPH to 70 MPH) it is also used to set the initial gear at 50 MPH to the top gear and hold it so that no shifting would occur.

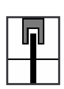
The Gear Box Program shifts the gears according to specified shift curves. The curves are given as a function of the load signal and the gear box output speed. The shapes of these curves constitute a compromise between CO_2 emissions, driveability, and performance and are representative of common industry practice. Once Gear Box efficiencies were obtained (see above), shift programs were adjusted to match EPA certification data for CO2 emissions on the study vehicle. The target gear determined by the gear box program is transmitted to the gear box control which in turn transmitted the desired gear to the gear box. The shift program was used for all cycle calculation tasks.

B.2.7. Axle 

The axle is represented by two components in CRUISE. A Single Ratio Transmission is used for the transmission ratio and torque losses in the axle. A differential splits the torque between the two output shafts and was set to be unlocked, i.e. differences in output shaft speeds were allowed. The axle ratio and efficiency for each of the vehicles are presented in Table B-4.

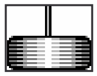
Table B-4: Axle Ratios and Efficiencies for each of the baseline vehicles

	Small Car	**Large Car**	**Minivan**	**Small Truck**	**Large Truck**
Ratio	3.63	3.98	3.62	4.10	3.73
Efficiency	0.97	0.96	0.98	0.94	0.975

B.2.8. Brakes 

During a cycle run, the energy for decelerating the vehicle is sometimes greater than what the engine and driveline can absorb. To make up for the difference, brake elements are included. The brakes were sized by taking the vehicle model and adjusting the piston size until the stopping distance of the vehicle was comparable to published data. This sizing was then held constant through the rest of the analyses.

B.2.9. Wheels

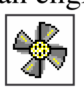


The wheels and tires link the vehicle to the road. As the rolling resistance is included in the EPA coefficients, the primary data input for the wheels are the rolling radius and the inertia. The standard tires specified for the vehicles were used to find the rolling radius on the websites of tire manufacturers. Appropriate inertia values were used. For the Full Load Accelerations and the climbing tasks, slip was considered. The longitudinal tire force (circumferential force) results from the friction coefficient, the wheel load, and the slip factor.

B.2.10. Auxiliaries

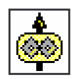
The auxiliaries are defined in the Mechanical Consumer elements in the CRUISE models. For each of the auxiliaries, an engine speed dependent torque loss is defined.

B.2.10.1. Alternator



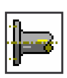
An electrical load of 300 W was applied to the vehicles during all simulations. An alternator torque loss was applied at the engine to account for the loss in all non-hybrid cases. The average alternator efficiency for the MY2002 baseline was approximately 60%. In some task 2 cases, this efficiency was increased to 80% to represent improvements predicted for the future. The cases using this higher efficiency alternator are specifically mentioned.

B.2.10.2. Automatic Transmission Oil Pump



The automatic transmission oil pump torque loss varied by vehicle. For the Large Truck, a variable displacement vane pump was assumed. The other vehicle classes had a torque loss curve for a fixed displacement pump. The pump losses were taken from "Design Practices, Passenger Car Automatic Transmissions 3rd Edition" pages 672 and 687 published by SAE. This pump was deleted on manual, automated manual, and CVT transmissions.

B.2.10.3. Starter



A starter element was added to CRUISE because of the soak (engine off) period in the FTP75, which requires that the engine be restarted. A Black Box control program was written to provide a torque signal to restart the engine. A torque of 75 Nm was added through a flange element until the engine speed reached 200RPM, when the engine received a start signal and began to power itself.

B.2.11. Anti-Slip Control

The Anti Slip Control element checked the Force Transmission Factor (Ratio between Force that should be transmitted and maximum transmittable Force) of all connected, driven wheels. If the torque transmitted to the wheels exceeded the maximum transferable force then the engine load signal was reduced. The control was used during the full load accelerations and climbing tasks in order to get a more realistic sense of the performance of the vehicle during climbing and accelerations. The difference between not considering slip (infinite traction) and inclusion of slip exceeded 1 second in the 0-60 MPH time.

B.3. Engine Technologies Investigated

Several advanced engine technologies were investigated during the project. Some were only studied in Task 1 to assess their potential contribution to greenhouse gas reduction. The more promising concepts also were selected for modeling in combination with other technologies in Task 2. These engine technologies are described below.

B.3.1. Baseline Multipoint Fuel Injection (MPFI)

The multipoint fuel injection engine was the baseline technology for all vehicles in the 2002 fleet because of its market dominance. In this technology, fuel is metered and injected in the intake ports of each cylinder. In combination with Exhaust Gas Recirculation (EGR), this fueling strategy provides a very cost effective and flexible means of engine control with a very good compromise of CO_2 and criteria exhaust emissions, and performance.

B.3.2. Variable Valve Timing / Cam Phasers (ICP, ECP, DCP, CCP)

Variable Valve Timing (VVT) is a very attractive technology that can enhance performance, while simultaneously reducing all exhaust emissions and fuel consumption. Engines equipped with an Intake Cam Phaser (ICP) are starting to take a moderate share of the market but have not reached a point of dominance and this technology was not included in any of the 2002 baseline vehicles. Intake Cam Phasers allow a better match of the intake valve event to different speeds and loads providing slightly higher and flatter torque curves and the ability to reduce throttling losses. Exhaust Cam Phasing (ECP) is being increasingly used as a performance enhancement technology but more importantly as a means of providing "Internal" EGR to reduce the emissions of NO_X and CO_2 (fuel consumption). Dual Cam Phasing combines the benefits of ICP and ECP and provides a significant improvement in performance (3-6%). Dual Cam Phasing also allows very flexible control of valve overlap, which can be used to aggressively reduce throttling losses, increase EGR, and lower NO_X/CO_2 emissions and fuel consumption. The VVT technologies previously described can only be used on engines equipped with Dual Overhead Camshafts (DOHC) since they control the intake or exhaust valves independently. On Single Overhead Camshaft (SOHC) or Overhead Valve (OHV) cam in block engines, independent intake or exhaust control is impossible. However, one Coupled Cam Phaser (CCP) can be used on these engines to control both intake and exhaust valves equally and much of the previously mentioned benefits can be obtained. Discrete engine maps were prepared for each of these four VVT configurations and were used in both Task 1 and Task 2 evaluations

B.3.3. Variable Valve Lift (DVVL, CVVL)

Engines equipped with a single intake cam lobe profile (those technologies described above) suffer an inherent compromise in that the optimum intake valve event varies with engine speed and load. At idle, an intake lobe with short duration, low lift, and minimal overlap is desired for the smoothest operation. At peak power, a cam lobe with high lift, long duration, and greater valve overlap is beneficial for maximum performance. Intermediate speeds and loads require values somewhere between these extremes. When an engine is forced to operate with a single cam lobe, function will be ideal at only one operating point and compromised at all others. While VVT offers some improvement in the required compromise, it is not as effective as having different valve lifts. Discrete Variable Valve Lift (DVVL) systems have been produced by Honda and Porsche and use two different intake cam lobes that are selected depending on engine speed and load. This can be used to improve performance or reduce emissions and fuel consumption. BMW has introduced a mechanical Continuous VVL (CVVL) system into production, which allows both higher performance and significantly reduced CO_2 emissions due to the reduction or elimination of throttling losses.

B.3.4. Variable Valve Actuation (EVA, EHVA)

Combining VVT and VVL yields the most flexible valve control. The most advanced versions of these Variable Valve Actuation (VVA) systems are Electromagnetic Valve Actuation (EVA) and Electro-Hydraulic Valve Actuation (EHVA). EVA is accomplished by using one electric actuator, like a solenoid or linear motor, per valve to control the valve's position. The electric actuator operates the valve, which at rest is positioned at mid-lift by two springs. The solenoid is excited at the correct frequency and duty cycle to open and close the valves at the appropriate times. EVA systems are limited to full valve lift but have nearly infinite flexibility in timing and duration and have faster response than the CVVL systems. These systems tend to be heavy and noisy and were not considered for inclusion in Task 2 simulations. Electro-Hydraulic systems offer the most flexibility of all the VVA systems. Valve timing, duration, lift, velocity, and acceleration are all controllable by the Electro-Hydraulic control valves and system pressure regulator. This system is an important enabler for some advanced combustion systems and was chosen for a number of cases in Task 2.

B.3.5. Turbocharging

Turbocharging uses waste thermal energy from the engine's exhaust gas stream to drive a turbine. A compressor mounted on the same shaft as the turbine is used to compress the intake air allowing a more dense charge to be delivered to the engine cylinder. Engine output can be increased significantly because of this pressurized intake air and as a result engine downsizing is possible. Under most operating conditions, the downsized engine operates at higher loads without boost, thereby reducing throttling losses. When power demand is high, the turbocharger comes into play to meet the required vehicle performance, effectively providing an engine with dual displacement. This technology has been used extensively on Diesel engines and high performance or racing gasoline engines. While turbocharging has not been used widely in the US passenger vehicle fleet, the potential for downsizing (on the order of 30%) can deliver an impressive reduction in CO_2 emissions and fuel consumption in certain vehicle applications.

B.3.6. Cylinder Deactivation (CYLDCT)

Cylinder Deactivation is another means of obtaining an engine with multiple displacements. For this technology, a relatively large engine is used at full displacement for high power demands. When the power demand is lower, a portion of the engine's cylinders (usually half) are turned off by disabling the intake and exhaust valves and the fuel injection system for the deactivated cylinders. In this way, a smaller engine (analogous to the downsized turbocharged engine) operates at higher load with reduced throttling losses, thereby lowering CO_2 emissions. This is a very cost effective technology for OHV engines and is most appropriate for vehicles like trucks, which can operate for extended periods of time at high loads (trailer tow, for example). While this concept can be applied on any engine with an even number of cylinders (Mitsubishi produced a four cylinder version in the past), it is practically limited to V8 engines because of vibration. A V6 engine could operate as a three cylinder engine when deactivated but customer acceptance is questionable unless extensive attention is paid to vibration isolation resulting in increased cost.

B.3.6.1. Cylinder Deactivation Control

The decision to enter into deactivation considers the current engine temperature, transmission ratio, torque, and whether the fuel consumption is less in deactivation or in full operation. The engine is not allowed to switch into deactivation if the engine temperature is less than 75°C. The fuel consumption of the full engine is compared to the fuel consumption of the deactivated engine. Deactivation is allowed in the region where the CO_2 emissions of the deactivated engine are lower than that of the full engine, provided the other criteria are met.

B.3.7. Variable Charge Motion

Variable charge motion uses active components in the intake system or valvetrain to create differing amounts of in-cylinder charge motion depending on engine speed and load. High charge motion at low speeds and light loads is beneficial for increasing the rate of combustion, which gives improved tolerance of lean combustion or high rates of EGR. This greater dilution tolerance can reduce CO_2 emissions because throttling losses can be decreased but also other emissions can be lowered due to faster exhaust catalyst "light-off." While rapid burn rate is desirable at light loads and could be delivered with non-variable components, volumetric efficiency at high speeds and loads could be adversely affected and the rate of cylinder pressure rise might be too high with such a fixed system. Consequently, variable charge motion systems have been developed to match the degree of charge motion to the engine speed and load. These dedicated systems are cost effective but most new engine designs can incorporate this technology in their basic design in combination with other technologies like VVT or VVL. For this reason, the technology was evaluated in Task 1 but not explicitly included in Task 2.

B.3.8. Variable Compression Ratio

Variable compression ratio is another technology that reduces CO_2 emissions. A high compression ratio at light loads can improve an engine's efficiency but would cause knocking and excessive cylinder pressures at high loads. Variable compression ratio avoids the inherent compromise of a fixed value and allows both lower CO_2 emissions and improved performance. Several systems have been proposed including complex linkages in the engine's cranktrain, variable height pistons, etc. These concepts are generally considered to be too complex and heavy for mass production and most of the benefits can be obtained with variable "effective" compression ratio through the use of cam phasers. For this reason, this technology was not evaluated in Task 2.

B.3.9. Gasoline Direct Injection (GDIS, GDILBS, GHCCI)

Gasoline Direct Injection (GDI) is a technology that has recently been introduced in mass production (1996) and has seen moderate market penetration in Japan and Europe. The preferred embodiment, Lean Burn Stratified Charge GDI (GDILBS), has not seen application in the US because it requires a Lean NO_X Aftertreatment system, the efficiency of which has not been sufficient to meet the stringent US NO_X emissions standards.

The first generation GDILBS systems tended to be "Wall Guided" designs. In these systems, the fuel spray was injected on to a "wall," a specially shaped surface of the piston, and then redirected toward the spark plug. This simple design creates a highly stratified mixture, which allows very lean mixtures to be burned, but suffers from relatively high HC emissions and the lean NO_X aftertreatment challenge described above. Second generation GDILBS systems are moving toward "Spray Guided" concepts, which address the HC emissions and further lower CO_2 emissions because of a larger lean operating range but still require lean aftertreatment systems. Considerable development activity on second generation GDILBS and Lean NO_X aftertreatment systems is ongoing and some applications could be seen in the US in the future.

Stoichiometric GDI systems (GDIS) avoid the aftertreatment difficulty faced by GDILBS but don't offer a large enough reduction in CO_2 emissions to justify their cost and have not seen broad application. However, with Tier 2 and LEV2 standards becoming increasingly more stringent, the precision cycle by cycle control of fuel delivery of these systems in combination with other CO_2 reduction technologies like Turbocharging or Cylinder Deactivation could make GDIS attractive.

Gasoline fueled Homogeneous Charge Compression Ignition (GHCCI) is listed as a GDI technology since the system will probably be built around GDI. HCCI has not yet proven feasibility across the full operating range of an engine so some alternative method of combustion (spark ignition, for example) will be required. For this project, AVL modeled the AVL CSI (Compression and Spark Ignition) engine. To obtain the flexibility in exhaust residual and cylinder temperature necessary for controlling HCCI combustion, CSI uses a cam phaser and discrete VVL on the intake and a simplified, limited range EHVA system on the exhaust. Fuel injection is by GDI and the cylinder head is otherwise a conventional 4-valve pent-roof combustion chamber with central spark plug for those operating conditions when autoignition is not possible or desirable. This is a very low NO_X and CO_2 combustion system that can operate with conventional 3-way catalyst.

B.3.10. Diesel (HSDI and Advanced Multi-mode)

Diesel combustion systems are very attractive because of their large reduction in CO_2 emissions and because of operating cost savings resulting from reduced fuel consumption. However, conventional high speed direct injection (HSDI) Diesel engines emit NO_X and particulate matter (PM) at rates that are too high for use in the US without aftertreatment. Diesel particulate filters with the required conversion efficiency have been developed and are in production but lean NO_X aftertreatment for Diesels faces the same challenge as GDILBS (described above). For this reason, Diesel engines have not seen broad acceptance in the US for passenger vehicle applications. For this project, AVL used engine maps for an engine equipped with 1800 bar common rail injection system capable of multiple injections per cycle for combustion and aftertreatment control. The engine also used a Variable Geometry Turbocharger (VGT) and cooled EGR and was developed to meet EURO 4/5 standards. Engine-out emissions levels were predicted and the required aftertreatment conversion efficiencies were used to define an appropriate aftertreatment system (the cost of which is described in Appendix B).

Homogeneous Charge Compression Ignition (HCCI) represents the ultimate goal for combustion engineers because there is no flame in HCCI combustion, so NO_X emissions are very low and the homogeneous charge avoids the formation of particulates. Diesel Advanced Multi-Mode refers to a Diesel-fueled version of HCCI or alternative combustion system. Full range operation of HCCI has not proven feasible and conventional HSDI is used at high loads and speeds and different alternative combustion modes with varying degrees of charge homogeneity are used at light loads. The alternative combustion processes are enabled by advanced common rail injection systems capable of precisely tailored multiple injections per cycle. Engine out emissions of NO_X and PM are significantly lower for this technology allowing a lower cost aftertreatment system. The CO_2 emissions reduction of DAMM is not quite as large as HSDI but still offers an improvement relative to gasoline fueled spark ignition engines.

B.4. Automatic Transmissions – 5, 6 Speeds

Automatic transmissions with more steps were considered as advanced powertrain systems. The changes from the baseline model included updating the gear box to the new gear sets and updating the shift and lock-up controls. The ratios for the new gear sets were taken from current production transmissions. The ratios were chosen based on drive types, FWD drive ratios for the cars and minivan, and RWD ratios for the trucks.

B.4.1. Changes to the Gear Box

Table B-5: Gear Ratios and Efficiencies for each of the vehicle classes for the 5AT

	Small Car		Large Car		Minivan		Small Truck		Large Truck	
	Ratio	η	Ratio	η	Ratio	η	Ratio	η	Ratio	η
Gear 1	3.938	0.955	3.55	0.95	3.938	0.955	3.57	0.945	3.55	0.95
Gear 2	2.194	0.955	2.24	0.95	2.194	0.955	2.20	0.945	2.24	0.95
Gear 3	1.411	0.97	1.54	0.93	1.411	0.965	1.51	0.925	1.54	0.93
Gear 4	0.973	0.97	1.0	0.98	0.973	0.975	1.0	0.975	1.0	0.98
Gear 5	0.703	0.985	0.69	0.965	0.703	0.985	0.80	0.96	0.69	0.965

Table B-6: Gear Ratios and Efficiencies for each of the vehicle classes for the 6AT

	Small Car		Large Car		Minivan		Small Truck		Large Truck	
	Ratio	η	Ratio	η	Ratio	η	Ratio	η	Ratio	η
Gear 1	4.044	0.96	4.044	0.96	4.044	0.96	4.171	0.96	4.171	0.96
Gear 2	2.371	0.975	2.371	0.975	2.371	0.975	2.34	0.975	2.34	0.975
Gear 3	1.556	0.96	1.556	0.96	1.556	0.96	1.521	0.96	1.521	0.96
Gear 4	1.159	0.975	1.159	0.975	1.159	0.975	1.143	0.975	1.143	0.975
Gear 5	0.852	0.96	0.852	0.96	0.852	0.96	0.867	0.96	0.867	0.96
Gear 6	0.672	0.975	0.672	0.975	0.672	0.975	0.691	0.975	0.691	0.975

B.4.2. Changes to the Torque Converter Lock-up

For the 5AT, torque converter lock-up was only allowed in 4^{th} and 5^{th} gears. The lock-up strategy was nearly identical to that of the 4AT because of the similarity in gear ratios. For the 6AT, lock-up was allowed in 4^{th} through 6^{th} gears and followed practices designed for the 4AT.

B.5. Manual Transmissions

For manual transmissions the torque converter is replaced by a dry clutch that is controlled by the driver through a clutch pedal. The clutch capacity was set to allow transmitting a maximum torque greater than the engine peak torque in order to prevent slipping when the clutch was engaged. Also, the automatic transmission oil pump was removed from the model.

Table B-7: Gear Ratios and Efficiencies for each of the vehicle classes for the 5MT

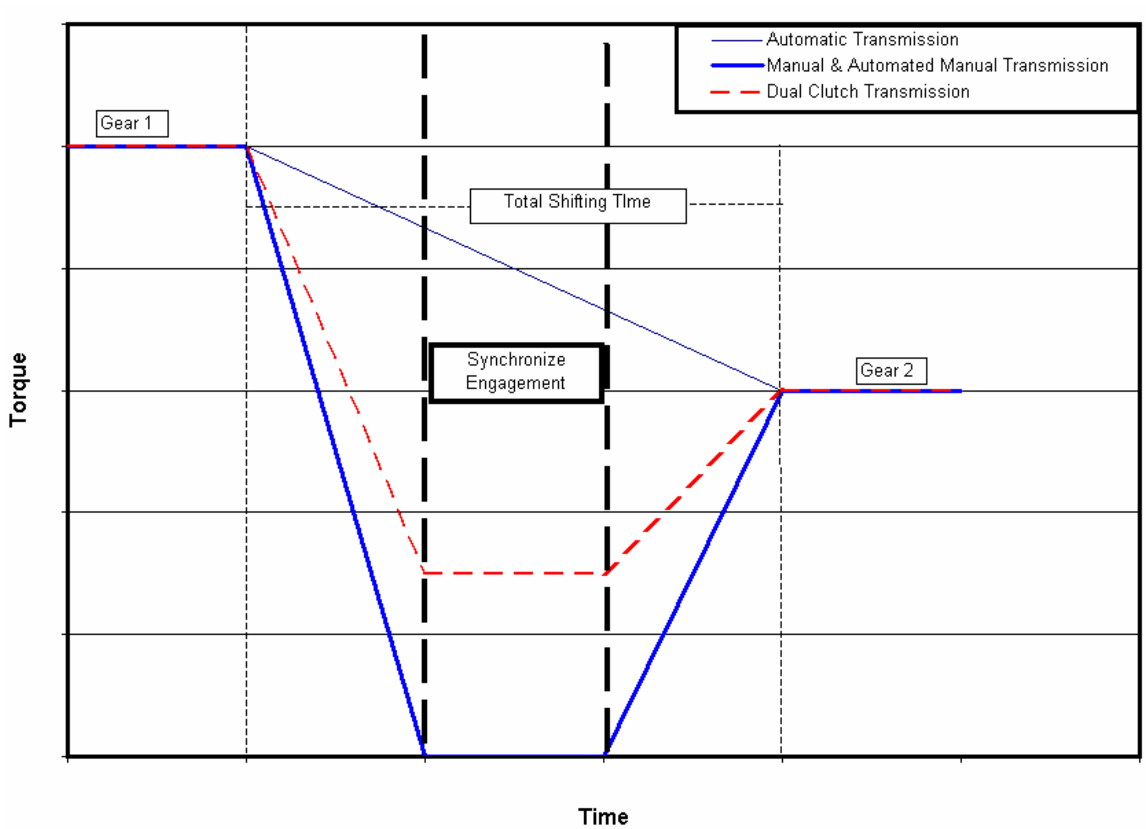
	Small Car		Small Truck	
	Ratio	η	Ratio	η
Gear 1	3.58	0.96	3.83	0.92
Gear 2	2.02	0.96	2.062	0.92
Gear 3	1.35	0.96	1.436	0.92
Gear 4	0.98	0.965	1.0	0.95
Gear 5	0.69	0.96	0.838	0.92

Shifts during the drive cycles were performed according to U.S. EPA's standard shift schedule. The velocity of the vehicle was reviewed to verify that the vehicle stayed within velocity limitations. If the vehicle could not follow the prescribed velocity profile, a downshift was added to successfully complete the test.

B.5.1. Driver Shifting Behavior

The gear shifting profile is presented in Figure B-4. The calculations of the acceleration rates include the temporary loss of drive torque due to the disengagement of the clutch and the time required to shift the gear. The torque provided during the engagement and release of the clutch is also included. The overall shift time was 0.5 seconds for a cycle run and 0.4 seconds during the full load acceleration.

Figure B-4: Shift Behavior of AT, and AMT, DCT transmissions



B.6. Automated Manual Transmissions

The automated manual transmissions were assumed to be 6 speed transmissions. The ratios also came from current production transmissions. The ratios were chosen based on the drive type (i.e. FWD 6 AMT ratios were chosen for the SC, LC and MV, and RWD ratios chosen for the trucks).

B.6.1. Changes to the gear box

Table B-8: Gear Ratios and Efficiencies for each of the vehicle classes for the 6AMT

	Small Car		Large Car		Minivan		Small Truck		Large Truck	
	Ratio	η	Ratio	η	Ratio	η	Ratio	η	Ratio	η
Gear 1	3.93	0.97	3.93	0.96	3.93	0.96	4.46	0.95	4.46	0.96
Gear 2	2.48	0.97	2.48	0.96	2.48	0.96	2.61	0.95	2.61	0.96
Gear 3	1.70	0.97	1.70	0.96	1.70	0.96	1.72	0.95	1.72	0.96
Gear 4	1.25	0.97	1.25	0.96	1.25	0.96	1.25	0.95	1.25	0.96
Gear 5	0.98	0.97	0.98	0.96	0.98	0.96	1.0	0.98	1.0	0.99
Gear 6	0.77	0.97	0.77	0.96	0.77	0.96	0.84	0.95	0.84	0.96

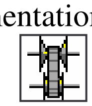
B.6.2. Auxiliary losses

An additional auxiliary was included to model the losses for the shifting mechanism. An electric shifting mechanism was assumed with average power consumption of 15 W over the cycle. This consumption was then adjusted by the alternator efficiency (see discussion above) to determine the torque loss for the mechanical consumer.

B.6.3. Shifting Behavior

Current AMT systems use hydraulic or electrical activation of the main clutch of a manual transmission so that the decision to shift is no longer controlled by the driver. The shift behavior of an AMT is similar to that of a manual driver, i.e. loss of torque occurs during the shift. New technologies are available to reduce the torque loss during the shift of an automated manual. The most prominent is a Dual Clutch Transmission (DCT). The DCT uses two clutches, split between the number of gears. When a shift is desired, the desired gear is brought to speed and the torque is added to the driveline by slipping one of the clutches. During the engagement of the new gear, the torque transmitted by the current gear is reduced by slipping the second clutch. In practice there is still a loss of torque during the shift when compared to the automatic transmission, shown in Figure B-4. As the U.S. market does not like the effect of the torque loss during the shift on driveability, a DCT is the form of an AMT that would have the best chance of market penetration. Future versions of the DCT include electric motors to augment the torque applied to the driveline during shifts. In this form, the shift behavior is more like that of an automatic transmission. The shift behavior for the AMT in the CRUISE models is that of an electrically augmented DCT, the loss of torque during the shift is not modeled, however the additional power requirement for the torque augmentation is not included.

B.7. Continuously Variable Transmission (CVT)



With the CVT gear box included in CRUISE, it is possible to vary the transmission ratio infinitely between two user defined threshold values. The CVT can convert every point on the engine's operating curve to an operating curve of its own, and every engine operating curve into an operating range within the field of potential driving conditions. The CVT's advantage over conventional fixed-ratio transmissions lies in the potential for enhancing performance, reducing operating cost due to lower fuel usage, and reduced exhaust emissions (by maintaining the engine at its operating point of maximum efficiency).

B.7.1. CVT Ratio Range

The CVT was only applied to FWD vehicles, i.e. Small Car, Large Car, and Minivan. The CVT had maximum and minimum ratios of 2.658 and 0.443. The response time required to shift between the maximum and minimum ratios was chosen to be 2 seconds.

B.7.2. CVT Losses

The CVT losses were obtained from testing done by the Technical University in Graz Austria under contract by AVL. This data is confidential but covered the transmission ratios used in the models. From the test data, empirical relations were created to determine the torque loss as a function of input speed, vehicle velocity, and torque.

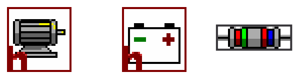
Two CVT efficiency maps were prepared for the models, one with a maximum torque input of 250 Nm (SC) and one with a maximum torque input of 320 Nm (LC, MV). The equations for the CVT losses are confidential, but average efficiencies for the smaller capacity CVT of 80% and for the larger capacity CVT of 75% are typical.

B.7.3. Control of the CVT

The CVT control element in CRUISE uses the vehicle velocity and load signal to determine what the CVT ratio should be. The generation of this control map was performed considering the individual vehicle parameters (axle ratio, tire radius), engine efficiency, full load curve, and the CVT maximum and minimum ratios.

For full throttle operation, the engine's full load curve was used to calculate the engine speed at which the most power was transferred to the axle. The CVT ratio was then chosen to provide that speed.

B.8. Hybrid Vehicles



The hybrid models in CRUISE were used to determine the performance levels of the vehicle. To predict the cycle CO2 emissions, the electric components were removed and an offline analysis was performed to subtract the CO2 emitted during idle operation as the engine would be shut-off during this time or when hybrid control would allow lower CO_2 emissions. The analysis method is described in section B.8.3.

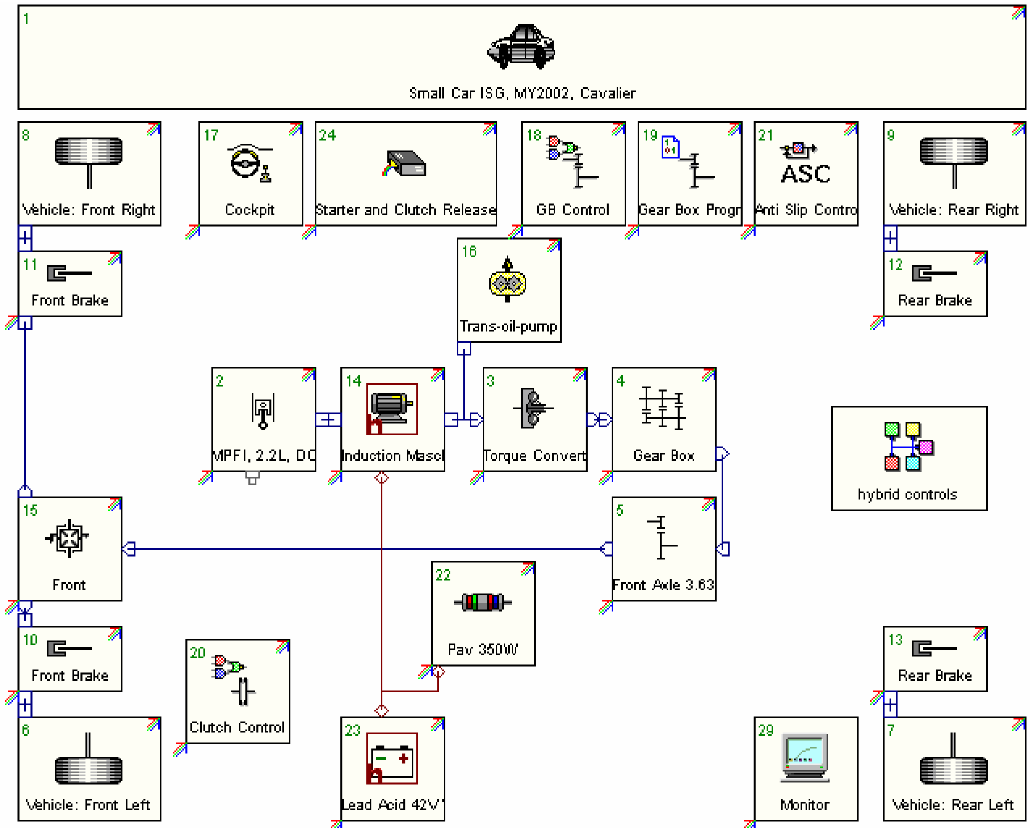
B.8.1. Hybrid Configurations

B.8.1.1. Integrated Starter Generators

The integrated starter generator hybrid contains a 10 kW electric motor placed between the engine and the torque converter or the clutch. The general layout of this system is seen in Figure B-5. The ISG hybrids are run on a 42V system and use a lead acid battery for energy storage. Two ISG control strategies were evaluated: Start Stop (42VSS) and Motor Assist (42VMA).

The alternator and starter were removed from the baseline model and replaced with an electrical induction motor and an electrical consumer. The electric motor allows the engine to shut down at idle, re-starts the engine and assists with the vehicle launch on the motor assist versions. For this reason, the starter flange, described above, was no longer required. The electrical load that was applied to the baseline vehicle as a mechanical loss in the alternator is now applied as an electrical consumer at the nominal 42V of the electrical system. The electrical consumer element requires that a resistance be defined as a function of voltage. The resistance was defined for a constant power loss throughout the cycle of 350 W. The electrical power consumption also includes the electrification of other auxiliary components such as the water pump and the power steering pump, when so specified. In Task 2, a special case of ISG was run for the small car. This version used a 4 kW electric motor operated by the accessory drive belt. This system, referred to as a Belt Alternator Starter (BAS) was designed to run on a lower cost 12 V system and could only function in Start Stop mode. No motor assist was possible in this configuration.

Figure B-5: Layout of an Integrated Starter Generator Hybrid Model



B.8.1.2. Moderate and Aggressive Hybrid Configurations

The moderate and aggressive hybrid vehicles were not modeled explicitly for this project because the extreme complexity of their control systems and the effort required for their optimal calibration was beyond the scope of the project.

B.8.2. Integration with Other Transmissions

The hybridization of a model involved the addition of the electric motor, battery, and electrical consumer to the baseline transmission model. Any controls required for the base transmission were maintained. In the case of an AMT, the torque converter was replaced with a clutch, which was controlled by the normal AMT clutch control.

B.8.3. Post-Processing Analysis to Determine Hybrid Impact on CO_2 Emissions

Full modeling and optimization of the various hybrid control strategies were beyond the scope of the project. Consequently, the theoretical CO_2 reduction potential of the different HEV configurations was evaluated using simulation results from AVL CRUISE and additional calculations performed in MS EXCEL. The CRUISE model was built with a conventional drivetrain but with the engine displacement adjusted to match the baseline performance level, while taking into account the power of the electrical motor. In order to estimate the potential, the speed and torque requirements of the driveline components throughout each cycle were used to identify driving modes where fuel consumption could be eliminated or reduced from the time history trace of the vehicle simulation. For example, during an idle period where the engine could be shut down, the amount of fuel consumed during that period of time was subtracted from the total fuel consumption as evaluated in the CRUISE simulation.

The following driving modes are distinguished:

- Vehicle stop: This mode is set when the velocity is zero. This status is used to determine the effect of a hybrid powertrain with Start/Stop functionality. The fuel consumed during engine idle periods at zero velocity was subtracted from the overall consumption.

- Vehicle braking event: This mode is identified when the vehicle velocity is above zero and the brake pedal is actuated (a CRUISE output). The braking event is divided into several parts (depending on the powertrain topology: Mild or Moderate) and their different possible braking power levels (10 kW or 30 kW). This event is used to determine the energy saving potential of regenerative braking. The braking energy recovered could then be used in either electrical assist or pure electrical driving (Moderate hybrid only).

  A fully automated electric braking system was assumed for the hybrid configurations. This means that the demanded braking energy could be distributed ideally between the electric motor and the mechanical brake system. The distribution was dependent on the operating conditions; i.e. low power braking events could be done purely by the electrical motors!

- Powertrain locked: torque or energy transfer through torque converter clutch or friction clutch - independent of the direction of energy transfer. In this mode, the engine or motor must provide torque to the driveline (energy consumed by fuel or from the battery).

The topology of the Moderate HEV allows engine shut-off and "simulation" of the fuel cut off braking torque of the engine using the E-motor to recover electrical energy to the storage battery. Depending on the vehicle and based on the typical behavior during fuel cut off braking, a significant amount of energy could be recovered.

After identifying the energy flow within the driveline and the driving modes, the calculation and integration values (e.g. fuel consumed during start/stop events) are combined and the CO_2 reduction potential (considering the different hybrid topologies) is estimated.

The steps in the analysis for the Start Stop System, the Mild Hybrid, and the Moderate Hybrid Powertrain are as follows:

1. Calculation of the average powertrain efficiency of the baseline vehicle, without HEV components and Start Stop operation for the *individual* cycle.
2. Calculation of the fuel consumption that could be eliminated by using a Start Stop Strategy.
3. Calculate the total driving energy at the wheels over the cycle.
4. Calculate the driving energy that could be recovered (braking and during engine fuel cut-off) considering the efficiencies of the electric motor and the battery.
5. Reduce total fuel consumption by subtracting the recuperated energy from the total mechanical driving energy and using the calculated cycle (individual) average powertrain efficiency.

Remarks:
1. For all calculations, auxiliary losses, electrical and mechanical efficiencies, etc. are considered. The calculations described above show the method of determining the potential for reduction of CO_2 emissions without specifically describing the losses.
2. The efficiency values for the electric motors and the battery system are from published data.

B.9. Other Technologies

Technologies other than transmission or engine technologies that influence CO_2 emissions and performance are included in this category. For the changes in the vehicle characteristics (mass, drag coefficient, rolling resistance), a physical model was built and correlated to the baseline data. This was done just for the small car and large truck models. In these physical calculation models, the EPA coefficients were removed and replaced with an appropriate aerodynamic drag coefficient, frontal area, and rolling resistance parameters.

B.9.1. Aerodynamic Drag

The effect of aerodynamic drag was determined by reducing the drag coefficient from the base value in steps of 0.02 until a final value of 0.1 less than the base was reached. The results were curve fit to determine a percent CO_2 reduction per percent change in drag coefficient.

B.9.2. Rolling Resistance

The rolling resistance was also reduced in five steps to 10% less than the baseline value. Similar to the drag coefficients, a curve fit was then performed to determine a percent CO_2 improvement per percent change in rolling resistance value.

B.9.3. Vehicle Mass

The vehicle mass was swept from ETW minus 250 lbm to ETW plus 250 lbm in steps of 50 lbm. The effect of the reduction in load on the rolling resistance was included. The results from the sweeps were used to create a coefficient for estimating the influence of mass on CO_2 emissions. No attempt to resize the engine to maintain baseline performance levels was made so the coefficients do not include this effect. In Task 2 small car simulations, the EPA coefficients were adjusted by this mass effect when called for.

B.9.4. Improved Alternator

For the time period investigated, 2009-2015, it was assumed that improvements in alternator efficiency could be expected. Current alternators operate with an average efficiency of about 60%. Higher efficiency alternators (approximately 80% average efficiency) are available currently but have not been implemented broadly because of their cost. Both conventional and higher efficiency alternators are modeled in CRUISE as engine speed dependent torque loads driven by the engine. The loads represent the torque required by the alternator to produce 350 W of electrical power during the test cycles.

B.9.5. Electrified Auxiliaries

With the exception of the alternator, AMT shift mechanism, and transmission oil pump, all of the auxiliaries are represented as torque losses on the engine motoring curve in the engine element of the CRUISE model.

B.9.5.1. Power Steering Pump

The torque required to drive the power steering pump with no steering loads applied for a typical vehicle in each of the classes was included in the base motoring curve. When Electric Power Steering (EPS) or Electro-Hydraulic Power Steering (EHPS) was specified for a model, this base torque loss was eliminated from the motoring curve. Since there are no steering inputs on the chassis dynamometer during an emissions test procedure, no additional losses were included and this represents a pure load reduction for the engine on the cycle runs.

B.9.5.2. Engine Oil Pump

The load to drive the engine oil pump was also included in the base motoring curve as described above. Oil pumps are traditionally sized to provide sufficient oil pressure on a high mileage engine at idle under high ambient temperature conditions. This results in significantly oversizing the pump causing it to operate in pressure relief under most operating conditions, thereby wasting energy. The next most severe operating condition for the oil pump is to supply sufficient oil pressure at full power. Sizing a pump for this condition reduces the pump displacement by about 30%. An electric oil pump can be used intermittently to handle the gap between this high power demand and the worn engine, hot idle demand. More aggressive downsizing of the oil pump requiring more active electric oil pump operation is possible but was not considered because of engine reliability effects. For this component, the reduction in load allowed by the 30% downsizing was subtracted from the engine motoring curve.

B.9.5.3. Engine Water Pump

Like the oil pump, engine coolant pumps are traditionally sized very conservatively to provide the required flow necessary to cool the engine under peak power conditions. At every other operating condition, the pump is significantly oversized and requires thermostatic control resulting in relatively high parasitic loads. Additionally, coolant flow could be eliminated or reduced drastically following an engine cold start allowing much faster warm-up with associated reduction in CO_2 and exhaust emissions. When considering that the water pump shouldn't operate during the first few minutes of a test cycle and then should operate at much lower flow rates than an engine driven pump, the reduction in power consumed is significant. For simplicity of modeling, this power was represented as a cycle average value and added to the alternator's continuous load.

B.9.6. Air Conditioning

Currently, air conditioning is not operated on the FTP75, Highway or US06 test cycles (there is a specific test cycle – SC03 to quantify the impact of air conditioning). However, the air conditioning compressor represents a significant load on the engine and since air conditioning is becoming nearly standard equipment in the US fleet, it was desired to quantify the air conditioning effect through simulation. Air conditioning compressor torque curves were provided by Meszler Engineering Services (MES) for use in these models and are described in more detail in Appendix D. Two air conditioning compressor technologies were evaluated: fixed displacement, and variable displacement with air recirculation. MES developed curves that represented the loads required to cool vehicles operating at US annual average ambient temperature and relative humidity conditions for each compressor type using R152a refrigerant. These loads were modeled as a continuous engine speed dependent torque requirement for the engine over the cycle and a control was added to drop the air conditioning compressor load if the driver demanded maximum acceleration.

B.10. Results

The project to assess GHG emissions reduction technologies was divided into several parts. In the first phase, baseline vehicle models in CRUISE were developed for each of the five vehicle classes. In the second step, the baseline models were used to evaluate selected individual engine, drivetrain, or vehicle technologies for their potential to reduce GHG emissions. In the final task, CRUISE models were created with combinations of promising technologies and the combined impacts were determined. The results from each of these project segments are described below.

B.10.1. Development of 2002 Baseline Vehicle Models

The US fleet for the 2002 Model Year (MY) was split into five classes: Small Car, Large Car, Minivan, Small Truck, and Large Truck. Statistical analyses of each class were performed and a production vehicle that, on average, represented the characteristics of the "homogeneous" class was selected. The following parameters were considered in the selection process: Curb Weight, Engine Displacement, Power, Power to Weight Ratio, Torque, Torque to Weight Ratio, City, Highway, and Combined Fuel Economy, etc. The production vehicles selected for each class and a comparison of the results of the baseline simulations to those vehicles' published data are shown in Table B-9. The calibration objective was to duplicate the actual vehicles' data within ± 1%.

B.10.2. Task 1 – Assessment of the Greenhouse Gas Reduction Potential of Individual Technologies

Once the baseline vehicle models were built and calibrated, they were used to evaluate the GHG reduction potential of several advanced engine, drivetrain, and vehicle technologies. Depending on the specific technology involved, the assessments were made in one of two ways. Engine technologies, where possible, were judged by comparing engine brake specific fuel consumption (BSFC) maps. All other technologies were reviewed by using a full CRUISE model equipped with the baseline engine.

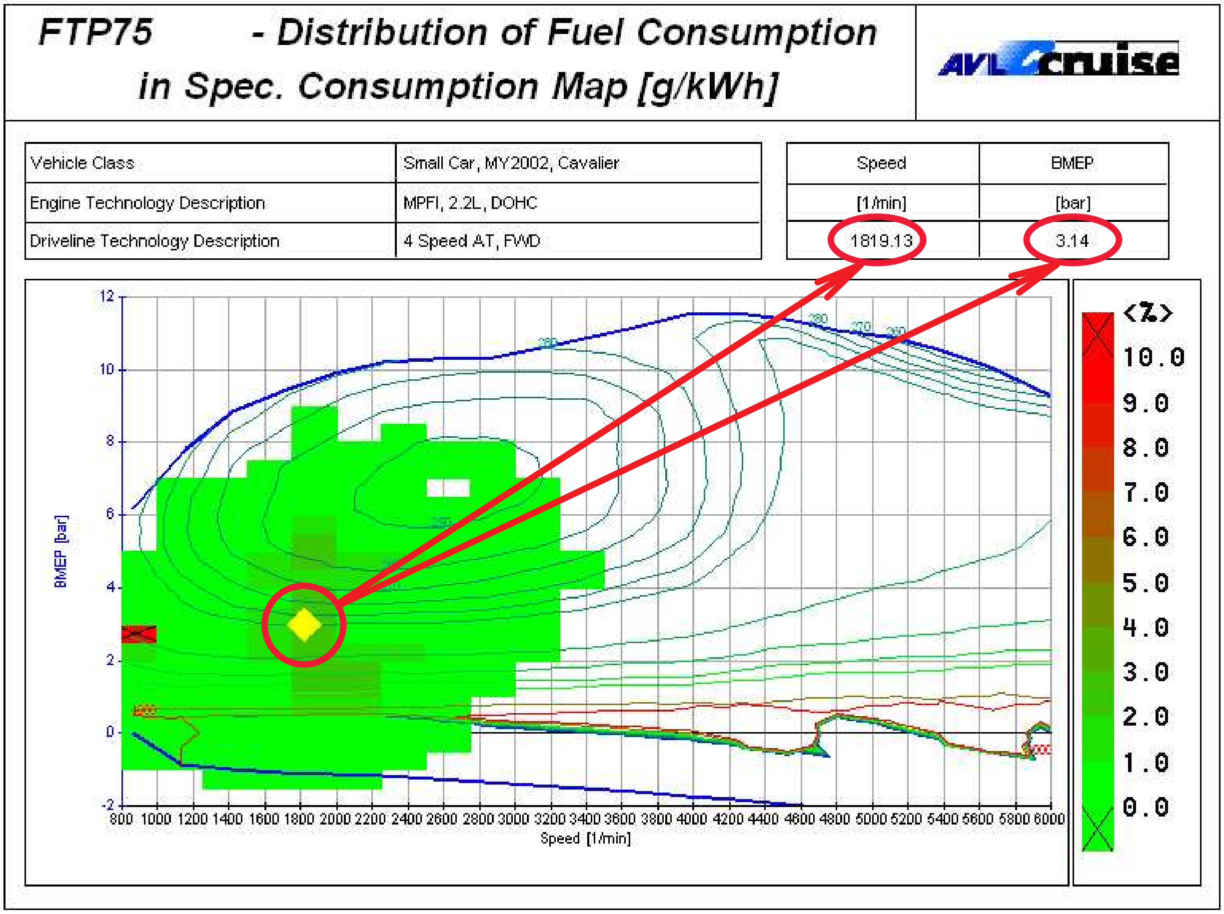
B.10.2.1. Task 1 - Assessment of the GHG Reduction Potential of Individual Engine Technologies

Typically, competitive engine technologies are evaluated by comparing BSFC at a standard speed and load point like 2000 RPM and 2 bar Brake Mean Effective Pressure (BMEP). While this method provides some insight into the "average" performance for all vehicles, it doesn't accurately describe the benefits expected for any one vehicle. In order to make the comparison of different engine maps more realistic, a single engine operating point most representative of each of the test cycles was determined for every baseline vehicle from the baseline CRUISE models. The process is shown graphically in Figure B-6. CRUISE determines a single, CO_2 emissions-weighted operating point that best approximates the average operating condition for the selected vehicle on the appropriate cycle. In the figure, this point is represented by the yellow diamond, the speed and load coordinates of which are also shown in the plot's table.

Table B-9: 2002 MY Baseline Vehicles

		FTP Unadjusted MPG		
Class	Representative Vehicle	Published Vehicle Data	CRUISE Model	Delta %
Small Car	Cavalier	26.5	26.3	-0.8%
Large Car	Taurus	22.1	22.3	0.9%
Minivan	Town & Country	19.6	19.6	0.0%
Small Truck	Tacoma	18.4	18.4	0.0%
Large Truck	Sierra	15.2	15.6	2.6%
		Highway Unadjusted MPG		
Small Car	Cavalier	41.5	41.5	0.0%
Large Car	Taurus	35.1	34.9	-0.6%
Minivan	Town & Country	30.7	30.4	-1.0%
Small Truck	Tacoma	24.0	24.2	0.8%
Large Truck	Sierra	21.9	21.7	-0.9%
		Combined Unadjusted MPG		
Small Car	Cavalier	31.6	31.5	-0.3%
Large Car	Taurus	26.5	26.6	0.4%
Minivan	Town & Country	23.4	23.3	-0.4%
Small Truck	Tacoma	20.6	20.6	0.0%
Large Truck	Sierra	17.6	17.9	1.7%
		0-60 Time [s]		
Small Car	Cavalier	8.2	8.74	6.6%
Large Car	Taurus	8.1	8.07	-0.4%
Minivan	Town & Country	N/A	10.48	
Small Truck	Tacoma	9.7	9.99	3.0%
Large Truck	Sierra	9.0	8.86	-1.6%

Figure B-6: Single Operating Point Determination



This analysis was conducted for each of the five baseline vehicles for both the FTP 75 (city) and Highway cycles. A summary of these operating points is shown in Table B-10.

Table B-10: Summary of Single Operating Points

2002 Representative Vehicle Data	Small Car	Large Car	Minivan	Small Truck	Large Truck
FTP 75 Cycle					
Engine Speed [1/min]	1995	2038	1864	1950	1483
Engine Load [bar]	2.74	2.13	2.95	2.72	2.74
CO_2 [g/mi]	319.9	382.9	426.0	456.0	534.8
Highway Cycle					
Engine Speed [1/min]	2188	2179	1837	2325	1526
Engine Load [bar]	3.19	2.63	3.69	3.45	3.70
CO_2 [g/mi]	204.4	242.3	276.0	350.9	391.4

An estimate of the potential reduction in CO_2 emissions on the FTP 75 for selected engine technologies is displayed in Table B-11. For each of these engine technologies, the BSFC at a vehicle's appropriate single point was compared to the baseline engine. Please note that the data in this table represent the improvements obtained at constant engine displacement. Some of these technologies improve specific output and would allow downsizing for additional reductions in CO_2.

Table B-11: Assessment of Individual Engine Technologies on FTP 75 Cycle

Vehicle Class	Small Car	Large Car	Minivan	Small Truck	Large Truck
Representative Vehicle	Cavalier	Taurus	Town & Country	Tacoma	Sierra
Engine	2.2l I4	3.0l V6	3.3l V6	3.4l V6	5.3l V8
Cam Phaser - Single (Intake)	-1%	-1%	-1%	-1%	-2%
Cam Phaser - Single (Exhaust)	-2%	-3%	-1%	-2%	-2%
Cam Phaser – Dual	-4%	-4%	-3%	-3%	-4%
Cam Phaser – Coupled	-3%	-4%	-2%	-3%	-4%
Variable Valve Lift – Discrete	-4%	-5%	-4%	-4%	-4%
Variable Valve Lift – Continuous	-5%	-7%	-4%	-5%	-6%
Camless Valve Actuation – Electrohydraulic	-13%	-17%	-14%	-14%	-14%
Turbocharging	-9%	-9%	-7%	-5%	
Cylinder Deactivation	-4%	-6%	-6%	-6%	-6%
Variable Charge Motion (CBR)	-3%	-4%	-2%	-3%	-4%
GDI Stoichiometric	1%	-1%	1%	1%	0%
GDI Lean Burn Stratified	-7%	-9%	-6%	-7%	-9%
Gasoline HCCI	-5%	-7%	-4%	-5%	-6%
Diesel – HSDI	-21%	-24%	-26%	-27%	-25%
Diesel – Advanced Multi-Mode	-16%	-18%	-21%	-22%	-20%

For those technologies (Turbocharging, Diesel, Cylinder Deactivation) with radically different full load curves or operating modes, the single point evaluation method was not meaningful. In these cases (shaded in the table), the estimates were obtained through full CRUISE simulations with engine displacements adjusted to maintain vehicle performance at the baseline level. The Camless Valve Actuation – Electrohydraulic technology included Cylinder Deactivation and the single point estimates were adjusted based on the results from a single vehicle simulation. Of additional note, the two Diesel improvement estimates are based on fuel consumption not CO_2 emissions. The true reduction in CO_2 emissions would be smaller because of Diesel fuel's higher density.

Table B-12: Assessment of Individual Engine Technologies on Highway Cycle

Vehicle Class	Small Car	Large Car	Minivan	Small Truck	Large Truck
Representative Vehicle	Cavalier	Taurus	Town & Country	Tacoma	Sierra
Engine	2.2l I4	3.0l V6	3.3l V6	3.4l V6	5.3l V8
Cam Phaser - Single (Intake)	-2%	-2%	-1%	-1%	-2%
Cam Phaser - Single (Exhaust)	-2%	-3%	-2%	-2%	-3%
Cam Phaser – Dual	-3%	-4%	-2%	-2%	-4%
Cam Phaser – Coupled	-3%	-4%	-2%	-2%	-4%
Variable Valve Lift – Discrete	-4%	-4%	-3%	-3%	-4%
Variable Valve Lift – Continuous	-4%	-6%	-3%	-4%	-4%
Camless Valve Actuation – Electrohydraulic	-9%	-15%	-8%	-12%	-9%
Turbocharging	-3%	-6%	-4%	-8%	
Cylinder Deactivation	-1%	-6%	-3%	-5%	-2%
Variable Charge Motion (CBR)	-3%	-4%	-3%	-4%	-4%
GDI Stoichiometric	-1%	-1%	1%	1%	0%
GDI Lean Burn Stratified	-5%	-8%	-3%	-2%	-6%
Gasoline HCCI	-3%	-6%	-2%	-2%	-4%
Diesel – HSDI	-19%	-19%	-22%	-27%	-21%
Diesel – Advanced Multi-Mode	-11%	-11%	-15%	-21%	-13%

Table B-12 and Table B-13 show the improvement potential of the individual engine technologies on the Highway cycle and Combined City/Highway cycles (weighted 55%/45%) respectively. The same notes apply to each of these tables.

On a combined city/highway basis, the Cam Phasing and CBR technologies offer improvements in the 2-4% range. Variable Valve Lift systems show slightly better results. Turbocharging and Cylinder Deactivation are both variable displacement technologies and offer reductions approaching 10%. Gasoline Direct Injection (Stratified) exhibits a similar decrease in CO_2. Electrohydraulic Valve Actuation reduces fuel consumption in the range of 15% and Diesels show the best improvements with 20+%.

Table B-13: Assessment of Individual Engine Technologies on Combined FTP 75 and Highway Cycles

Vehicle Class	Small Car	Large Car	Minivan	Small Truck	Large Truck
Representative Vehicle	Cavalier	Taurus	Town & Country	Tacoma	Sierra
Engine	2.2l I4	3.0l V6	3.3l V6	3.4l V6	5.3l V8
Cam Phaser - Single (Intake)	-2%	-1%	-1%	-1%	-2%
Cam Phaser - Single (Exhaust)	-2%	-3%	-2%	-2%	-3%
Cam Phaser – Dual	-3%	-4%	-2%	-3%	-4%
Cam Phaser – Coupled	-3%	-4%	-2%	-2%	-4%
Variable Valve Lift – Discrete	-4%	-4%	-3%	-4%	-4%
Variable Valve Lift – Continuous	-5%	-6%	-4%	-5%	-5%
Camless Valve Actuation – Electrohydraulic	-11%	-16%	-11%	-13%	-12%
Turbocharging	-6%	-8%	-6%	-6%	
Cylinder Deactivation	-3%	-6%	-5%	-6%	-4%
Variable Charge Motion (CBR)	-3%	-4%	-2%	-3%	-4%
GDI Stoichiometric	0%	-1%	1%	1%	0%
GDI Lean Burn Stratified	-6%	-9%	-4%	-5%	-8%
Gasoline HCCI	-4%	-6%	-3%	-4%	-5%
Diesel – HSDI	-20%	-22%	-24%	-27%	-23%
Diesel – Advanced Multi-Mode	-13%	-15%	-18%	-21%	-17%

B.10.2.2. Task 1 – Assessment of the GHG Reduction Potential of Individual Drivetrain and Other Vehicle Technologies

The influence of advanced transmission or other vehicle technologies on CO_2 emissions is more complicated and could not be assessed using a single point comparison of engine maps. More specifically, when designed properly, advanced transmissions shift the operating point of the engine to more efficient areas of the map. For this reason, full CRUISE simulations were required to determine the improvement potential of these vehicle related technologies. In order to isolate the effect of individual technologies, the baseline engine was used in each case. No attempt was made to correct for any improvement or change in vehicle performance compared to the baseline vehicle.

The CO_2 improvement potential of selected drivetrain technologies on the city cycle is shown in Table B-14. The baseline drivetrain for each vehicle was a 4-speed Automatic Transmission with lock-up Torque Converter. Engine displacement was held constant as described above. The 5-speed Manual was shifted according to the US EPA standard shift schedule. All other Automatics utilized shift curves developed and calibrated on the baseline vehicle. The reduction in fuel consumption afforded by the hybrid drivetrains was determined through post-processing of CRUISE results.

Table B-14: Assessment of Individual Drivetrain Technologies on FTP 75 Cycle

Vehicle Class	Small Car	Large Car	Minivan	Small Truck	Large Truck
Representative Vehicle	Cavalier	Taurus	Town & Country	Tacoma	Sierra
Engine	2.2l I4	3.0l V6	3.3l V6	3.4l V6	5.3l V8
5-Speed Automatic	-2%	-1%	-1%	-1%	-1%
6-Speed Automatic	-3%	-4%	-5%	-4%	-2%
6-Speed Automated Manual	-12%	-10%	-11%	-10%	-9%
5-Speed Manual	-4%			-1%	
CVT Transmission	-8%	-7%	-10%		
42-Volt 10 kW ISG (Start Stop)	-12%	-8%	-7%	-7%	-9%
42-Volt 10 kW ISG (Mot. Assist)	-17%	-10%	-10%	-10%	-10%

The improvement of these drivetrain technologies on the highway and combined city/highway cycles are presented in Table B-15 and Table B-16 respectively. As seen in Table B-15, most of the drivetrain technologies don't offer much improvement on the highway because the torque converter is locked for most of the cycle. Similarly, the lack of transients on this cycle limits the ability of the hybrids to recover braking energy.

Table B-15: Assessment of Individual Drivetrain Technologies on Highway Cycle

Vehicle Class	Small Car	Large Car	Minivan	Small Truck	Large Truck
Representative Vehicle	Cavalier	Taurus	Town & Country	Tacoma	Sierra
Engine	2.2l I4	3.0l V6	3.3l V6	3.4l V6	5.3l V8
5-Speed Automatic	-1%	-1%	-1%	-1%	0%
6-Speed Automatic	-2%	-2%	-1%	-3%	-1%
6-Speed Automated Manual	-3%	-4%	-4%	-5%	-1%
5-Speed Manual	-1%			-2%	
CVT Transmission	2%	1%	3%		
42-Volt 10 kW ISG (Start Stop)	0%	0%	0%	0%	0%
42-Volt 10 kW ISG (Mot. Assist)	-1%	-1%	-1%	0%	0%

Table B-16: Assessment of Individual Drivetrain Technologies on Combined FTP 75 and Highway Cycles

Vehicle Class	Small Car	Large Car	Minivan	Small Truck	Large Truck
Representative Vehicle	Cavalier	Taurus	Town & Country	Tacoma	Sierra
Engine	2.2l I4	3.0l V6	3.3l V6	3.4l V6	5.3l V8
5-Speed Automatic	-2%	-1%	-1%	-1%	-1%
6-Speed Automatic	-3%	-3%	-3%	-3%	-2%
6-Speed Automated Manual	-8%	-7%	-8%	-8%	-5%
5-Speed Manual	-2%			-1%	
CVT Transmission	-4%	-3%	-4%		
42-Volt 10 kW ISG (Start Stop)	-7%	-4%	-4%	-4%	-5%
42-Volt 10 kW ISG (Mot. Assist)	-10%	-6%	-6%	-6%	-5%

Overall, the trend to greater numbers of speeds in the automatic transmission is beneficial. The use of 6-speed automatics could improve combined CO_2 emissions by about 3%. Six-speed automated manuals are even better with reductions approaching 8% due to the elimination of the inefficiency of the torque converter. Conventional manual transmissions can offer the same improvement if shifted optimally but are not expected to take a major share of the US market. CVT transmissions offer some benefit but are hampered by losses in the belt drive system and similar improvements could be obtained less expensively with some of the other drivetrains. Hybrid drivetrains have an outstanding potential to reduce fuel consumption on the city cycle due to the ability to recuperate braking energy but much of the advantage is lost on the highway cycle resulting in combined improvements in the 5-10% range for the hybrid systems evaluated.

The final part of Task 1 was to investigate the contribution of “Other Vehicle” technologies that could not be grouped readily with the engine or drivetrain areas. Some examples include Air Conditioning, Electric Accessories, Aerodynamic Drag, etc. The CO_2 emissions impacts of these technologies on the city cycle are shown in Table B-17.

Please note that the last three technologies, Aerodynamic Drag, Mass, and Tire Rolling Resistance were modeled physically. Rather than using the published A, B, and C coefficients of the EPA chassis dynamometer setting to define vehicle resistance, the baseline models were converted to full physical models capturing drag coefficient, vehicle frontal area, tire rolling resistance, etc. The variables for these models were adjusted up and down from the baseline case by 5-10% and impact coefficients were determined through regression for each of these factors. These coefficients were in the form of % change in CO_2 per % change in the parameter. This would allow continuous variation of these parameters rather than in discrete steps like engine or drivetrain technologies. All of the other technologies were evaluated only on the small car and large truck. Since the improvements were quite close for the two extremes of vehicle types, it was concluded that the estimated improvements of all of the technologies could be applied to any vehicle.

Table B-17: Assessment of Individual Other Vehicle Technologies on FTP 75 Cycle

Vehicle Class	Small Car	Large Car	Minivan	Small Truck	Large Truck
Representative Vehicle	Cavalier	Taurus	Town & Country	Tacoma	Sierra
Engine	2.2l I4	3.0l V6	3.3l V6	3.4l V6	5.3l V8
Electric Power Steering (EPS)	-2%				-1%
Higher Efficiency Alternator	-1%				-1%
Electric Water Pump (EWP)	0%				0%
Electric Oil Pump (EOP)	0%				0%
Electric Accessories	-3%				-3%
Variable Displacement AC Compressor (vs. Fixed Displ.)	-12%	-10%	-8%	-11%	
Aerodynamic Drag Coefficient (% CO_2 / % Cd)	0.0442				0.0868
Mass Reduction Coefficient (%CO_2 / % Mass Change)	0.4424				0.4992
Tire Rolling Resistance Coefficient (% CO_2 / % TRR)	0.1343				0.1447

The highway cycle and combined cycle effects of the other vehicle technologies are displayed in Table B-18 and Table B-19 respectively. On a combined basis, the electric accessory technologies have a fairly small impact (1-2%) but could be applied to all vehicles. The Variable Displacement Air Conditioning Compressor shows an impressive reduction of about 10% in CO_2 in comparison to the Fixed Displacement Compressor. In current testing procedures, air conditioning is not used on the FTP 75 or Highway emissions cycles so no benefit would be obtained on the cycles. However, these benefits could be observed in real world driving. The impact coefficients for Aerodynamic Drag, Mass Reduction, and Tire Rolling Resistance agree reasonably well with results published in the literature. For example, a 5% reduction in mass would reduce CO_2 emissions by about 3%.

Table B-18: Assessment of Individual Other Vehicle Technologies on Highway Cycle

Vehicle Class	Small Car	Large Car	Minivan	Small Truck	Large Truck
Representative Vehicle	Cavalier	Taurus	Town & Country	Tacoma	Sierra
Engine	2.2l I4	3.0l V6	3.3l V6	3.4l V6	5.3l V8
Electric Power Steering (EPS)	-1%				-1%
Higher Efficiency Alternator	-1%				0%
Electric Water Pump (EWP)	0%				0%
Electric Oil Pump (EOP)	0%				0%
Electric Accessories	-2%				-2%
Variable Displacement AC Compressor (vs. Fixed Displ.)	-8%	-8%	-6%	-7%	
Aerodynamic Drag Coefficient (% CO_2 / % Cd)	0.3124				0.3200
Mass Reduction Coefficient (%CO_2 / % Mass Change)	0.6302				0.6582
Tire Rolling Resistance Coefficient (% CO_2 / % TRR)	0.2353				0.2755

Table B-19: Assessment of Individual Other Vehicle Technologies on Combined FTP 75 and Highway Cycles

Vehicle Class	Small Car	Large Car	Minivan	Small Truck	Large Truck
Mule Vehicle	Cavalier	Taurus	Town & Country	Tacoma	Sierra
Engine	2.2l I4	3.0l V6	3.3l V6	3.4l V6	5.3l V8
Electric Power Steering (EPS)	-1%				-1%
Higher Efficiency Alternator	-1%				0%
Electric Water Pump (EWP)	0%				0%
Electric Oil Pump (EOP)	0%				0%
Electric Accessories	-3%				-2%
Variable Displacement AC Compressor (vs. Fixed Displ.)	-10%	-9%	-7%	-9%	
Aerodynamic Drag Coefficient (% CO_2 / % Cd)	0.1649				0.1917
Mass Reduction Coefficient (%CO_2 / % Mass Change)	0.5269				0.5708
Tire Rolling Resistance Coefficient (% CO_2 / % TRR)	0.1798				0.2036

B.10.3. Task 2 – Assessment of the Greenhouse Gas Reduction Potential of Combinations of Technologies

Upon completion of Task 1, a large number of individual engine, drivetrain, and vehicle technologies were evaluated and ranked for their potential to reduce GHG emissions. Some previous studies on the topic of GHG reduction combined separate technologies into "packages" and estimated the combined benefit by adding the individual technology improvements together. It is generally understood that combining improvement estimates in this way results in "double counting" or over-prediction of the actual reductions possible. To avoid this source of inaccuracy, selected technology combination packages were built as full CRUISE vehicle models and simulated in a more appropriate way. Since the number of possible combinations of all the technologies evaluated was enormous, the ranking of the Task 1 results together with estimates of the incremental cost of a technology was used to select reasonable and cost effective packages to simulate. The results of these technology simulations are described in the next section and the following tables.

B.10.3.1. Task 2 – Small Car Combinations of Technologies

Table B-20 displays the simulation results of 16 technology combinations compared to the 2002 MY baseline data. Case 00 represents a quasi-baseline for the 2009 MY. It represents the combination of technologies projected to take the largest share of the market in the small car class in 2009. This case was also used to capture projected changes in vehicle mass and performance in 2009.

The table contains the following information: Case Number, Technologies selected, adjusted Engine Displacement to match 2009 baseline performance levels, Fuel Economy on the FTP 75, Highway, and Combined cycles, Tier 2 Bin 5 tailpipe CO_2 emissions for the same cycles, and 0-60 MPH times. The same data is plotted graphically in Figures A-7 and A-8. Figure B-7 shows the combined cycle tailpipe CO_2 emissions, sorted in decreasing order. The 2009 baseline case (00) emits about 270 g/mi. As can be seen, the most effective technologies (GDI, Diesel, and Hybrids) are clustered near the bottom of the plot. The percentage reduction in combined CO_2 emissions of each package compared to the 2002 MY baseline vehicle is shown in Figure B-8. Improvements of 15-20% are possible with combinations of currently available engine and drivetrain technologies. Further reductions (>20%) require the use of hybrid technologies.

B.10.3.2. Task 2 – Large Car Combinations of Technologies

Table B-21 displays the simulation results of 23 technology combinations compared to the 2002 MY baseline data. Case 00 again represents a quasi-baseline for the 2009 MY. Figures A-9 and A-10 plot graphically the tabular values for combined tailpipe CO_2 emissions and percent reduction in combined CO_2 emissions. Like the small car class, relatively conventional technology combinations can yield reductions of 10-20%. Hybrids or advanced technology like Electro-Hydraulic Valve Actuation must be used to obtain improvements greater than 20%.

B.10.3.3. Task 2 – Minivan Combinations of Technologies

Table B-22 presents the simulation results of 13 technology combinations compared to the 2002 MY baseline data. Fewer cases were evaluated for the minivan class because the market share for this class is relatively small. The combined tailpipe CO_2 emissions level of the

2009 MY baseline model is approximately 350 g/mi. The best packages assessed were just under 300 g/mi for two Gasoline Direct Injection systems. Figures A-11 and A-12 plot graphically the tabular values for combined tailpipe CO_2 emissions and percent reduction in combined CO_2 emissions. Like the previous classes, relatively conventional technology combinations can yield reductions of 10-20%. Hybrids or advanced technology like EHVA must be used to obtain improvements greater than 20%. A Mild Hybrid (42VMA) with GDI demonstrated the largest reduction in CO_2 emissions (22%).

B.10.3.4. Task 2 – Small Truck Combinations of Technologies

Table B-23 displays the simulation results of 13 technology combinations compared to the 2002 MY baseline data. On the combined cycle, the 2009 baseline emits nearly 390 g/mi of CO_2. Fewer cases were modeled on the small truck compared to some of the other classes but the best case, a Diesel with 6-speed automated manual transmission, delivered a reduction of about 27%. Figures A-13 and A-14 show the data in graphical format. Readily available technologies can deliver improvements in the 10-20% range. Larger reductions in CO_2 require hybrid or other advanced technologies.

B.10.3.5. Task 2 – Large Truck Combinations of Technologies

The simulation results of 16 technology packages on the large truck are shown in Table B-24. The combined CO_2 emissions for the 2009 MY baseline were just over 460 g/mi. The table data is plotted graphically in Figures A-15 and A-16. Combinations of conventional technologies, including simple mass reduction, could reduce CO_2 emissions by 10-20%. More advanced technologies, like hybrid drivetrain or EHVA, are required to achieve more than 20% improvement.

Table B-20: Small Car Technology Combination Simulation Results

Small Car Technology Combination Simulation Results			Tier 2 Bin 5 CO_2 [g/mi]				0-60 MPH
Simulation	Technology	Displ. [l]	FTP	HWY	Comb.	Delta %	[s]
MY 02 B/L	MPFI,4AT	2.20	332.6	211.0	277.9	0.0%	8.74
Case 00	DCP,DVVL,5AT	2.20	316.6	213.9	270.4	-2.7%	8.08
Case 01	DCP,6AT	2.10	313.1	210.3	266.8	-4.0%	8.07
Case 02	DCP,4AT,EPS,HIALT	2.30	325.8	216.2	276.5	-0.5%	8.07
Case 03	DCP,5AT,EPS,HIALT	2.20	313.2	210.8	267.1	-3.9%	8.08
Case 04	DCP,CVT,EPS,HIALT	2.40	311.1	228.1	273.8	-1.5%	8.01
Case 05	DCP,DVVL,6AMT,EPS,HIALT	2.20	269.1	201.7	238.8	-14.1%	8.08
Case 06	GHCCI,6AMT,EPS,HIALT	2.10	263.7	197.1	233.7	-15.9%	8.08
Case 07	DCP,TURB,GDIS,6AMT,EPS,HIALT	1.18	239.4	194.1	219.0	-21.2%	8.09
Case 08	GHCCI,6AMT,42VMA,EPS,EWP,EOP	1.92	222.2	190.8	208.1	-25.1%	8.13
Case 10	DAMM,6AMT,42VMA,EPS,EWP,EOP	1.72	230.7	208.4	220.7	-20.6%	8.09
Case 13.1	DCP,TURB,GDIS,6AMT,EPS,HIALT,FIXAC	1.18	306.8	226.4	270.6	-2.6%	8.09
Case 13.2	DCP,TURB,GDIS,6AMT,EPS,HIALT,VARAC	1.18	270.3	209.3	242.9	-12.6%	8.09
Case 14	DCP,CVVL,6AMT,12VSS,EPS	2.20	240.4	197.2	221.0	-20.5%	8.08

Technology Key

DCP	Cam Phaser - Dual	6AMT	6-Speed Automated Manual
CCP	Cam Phaser - Coupled	CVT	Continuously Variable Transmission
DVVL	Variable Valve Lift - Discrete	12VSS	12-Volt 4 kW ISG (Start Stop)
CVVL	Variable Valve Lift - Continuous	42VMA	42-Volt 10 kW ISG (Motor Assist)
EHVA	Camless Valve Actuation - Electrohydraulic	EPS	Electric Power Steering
TURB	Turbocharging	HIALT	Improved Alternator (Higher efficiency)
CYLDCT	Cylinder Deactivation	EWP	Electric Water Pump
GDIS	GDI Stoichiometric	EOP	Electric Oil Pump
GDILBS	GDI Lean Burn Stratified	FIXAC	Fixed Displacement AC Compressor
GHCCI	Gasoline HCCI	VARAC	Variable Displacement AC Compressor
HSDI	Diesel	MR	Mass Reduction
DAMM	Diesel – Advanced Multi-Mode		
5AT	5-Speed Automatic		
6AT	6-Speed Automatic		

Table B-21: Large Car Technology Combination Simulation Results

Large Car Technology Combination Simulation Results			Tier 2 Bin 5 CO_2 [g/mi]				0-60 MPH
Simulation	Technology	Displ. [l]	FTP	HWY	Comb.	Delta %	[s]
MY 02 B/L	MPFI,4AT	3.00	392.7	251.7	329.2	0.0%	8.07
Case 00	DCP,DVVL,6AT	3.00	362.7	237.9	306.5	-6.9%	7.24
Case 01	DCP,CYLDCT,6AT	3.00	349.2	225.9	293.7	-10.8%	7.24
Case 02	DCP,CVVL,6AT	3.00	349.9	232.8	297.2	-9.7%	7.24
Case 03	DCP,6AT	3.00	370.4	240.5	311.9	-5.3%	7.24
Case 04	DCP,TURB,6AT,EPS,HIALT	1.67	335.6	224.2	285.5	-13.3%	7.23
Case 05	DCP,CVVL,6AMT,EPS,HIALT	3.00	311.5	221.1	270.8	-17.7%	6.80
Case 06	GHCCI,6AMT,EPS,HIALT	3.00	322.4	225.2	278.7	-15.4%	6.80
Case 07	DCP,TURB,GDIS,6AMT,EPS,HIALT	1.77	287.9	217.6	256.3	-22.2%	7.28
Case 08	DCP,CVT,EPS,HIALT	3.20	357.1	247.2	307.6	-6.6%	7.22
Case 09	DCP,TURB,GDIS,6AT,42VMA,EPS,EWP,EOP	1.34	245.6	205.6	227.6	-30.9%	7.24
Case 10	CCP,DVVL,CYLDCT,6AT,42VMA,EPS,EWP,EOP	2.86	289.8	235.3	265.3	-19.4%	7.25
Case 11	GHCCI,6AMT,42VMA,EPS,EWP,EOP	2.55	256.8	209.6	235.6	-28.5%	7.26
Case 12	DAMM,6AMT,42VMA,EPS,EWP,EOP	2.33	260.9	221.5	243.2	-26.1%	7.25
Case 16.1	DCP,TURB,6AT,EPS,HIALT,FIXAC	1.67	392.2	256.1	331.0	0.5%	7.23
Case 16.2	DCP,TURB,6AT,EPS,HIALT,VARAC	1.67	364.8	239.7	308.5	-6.3%	7.23
Case 17	DCP,CYLDCT,GDIS,6AMT,EPS,HIALT	2.70	315.7	215.7	270.7	-17.8%	7.26
Case 18.1	DCP,CYLDCT,GDIS,6AMT,EPS,HIALT,FIXAC	2.70	380.1	253.7	323.2	-1.8%	7.25
Case 18.2	DCP,CYLDCT,GDIS,6AMT,EPS,HIALT,VARAC	2.70	342.9	233.1	293.5	-10.9%	7.25
Case 19	EHVA,6AMT,EPS,HIALT	3.00	296.1	206.4	255.7	-22.3%	6.88
Case 20	EHVA,GDIS,6AMT,EPS,HIALT	2.70	283.0	202.3	246.7	-25.1%	7.25

Technology Key

DCP	Cam Phaser - Dual	6AMT	6-Speed Automated Manual
CCP	Cam Phaser - Coupled	CVT	Continuously Variable Transmission
DVVL	Variable Valve Lift - Discrete	42VSS	42-Volt 10 kW ISG (Start Stop)
CVVL	Variable Valve Lift - Continuous	42VMA	42-Volt 10 kW ISG (Motor Assist)
EHVA	Camless Valve Actuation - Electrohydraulic	EPS	Electric Power Steering
TURB	Turbocharging	HIALT	Improved Alternator (Higher efficiency)
CYLDCT	Cylinder Deactivation	EWP	Electric Water Pump
GDIS	GDI Stoichiometric	EOP	Electric Oil Pump
GDILBS	GDI Lean Burn Stratified	FIXAC	Fixed Displacement AC Compressor
GHCCI	Gasoline HCCI	VARAC	Variable Displacement AC Compressor
HSDI	Diesel	MR	Mass Reduction
DAMM	Diesel – Advanced Multi-Mode		
5AT	5-Speed Automatic		
6AT	6-Speed Automatic		

Table B-22: Minivan Technology Combination Simulation Results

Minivan Technology Combination Simulation Results			Tier 2 Bin 5 CO_2 [g/mi]				0-60 MPH
Simulation	Technology	Displ. [l]	FTP	HWY	Comb.	Delta %	[s]
MY 02 B/L	MPFI,4AT	3.30	447.8	289.2	376.4	0.0%	10.48
Case 00	CCP,DVVL,5AT	3.24	413.7	274.4	351.0	-6.7%	9.18
Case 01	DCP,6AT	3.25	419.6	279.9	356.7	-5.2%	9.18
Case 02	CCP,DVVL,6AMT,EPS,HIALT	3.06	370.5	263.6	322.4	-14.3%	9.17
Case 03	CCP,CVVL,6AMT,EPS,HIALT	3.06	356.4	258.1	312.2	-17.1%	9.17
Case 04	DCP,TURB,GDIS,6AMT,EPS,HIALT	1.85	336.9	262.2	303.3	-19.4%	9.16
Case 05	CCP,DVVL,CYLDCT,6AMT,EPS,HIALT	3.06	357.9	258.8	313.3	-16.8%	9.17
Case 06	CCP,CYLDCT,GDIS,6AMT,EPS,HIALT	2.90	376.7	263.4	325.7	-13.5%	9.09
Case 07	CCP,TURB,6AMT,EPS,HIALT	1.89	364.7	270.1	322.1	-14.4%	9.18
Case 08	DAMM,6AMT,EPS,HIALT	2.43	336.1	271.1	306.9	-18.5%	9.16
Case 09.1	CCP,CYLDCT,GDIS,6AMT,EPS,HIALT,FIXAC	2.90	458.5	308.4	391.0	3.9%	9.09
Case 09.2	CCP,CYLDCT,GDIS,6AMT,EPS,HIALT,VARAC	2.90	411.8	284.2	354.4	-5.9%	9.09
Case 10	CCP,CYLDCT,GDIS,6AMT,42VMA,EPS,EWP,EOI	2.60	322.6	255.2	292.3	-22.4%	9.14
Case 11	EHVA,GDIS,6AMT,EPS,HIALT	2.85	336.4	246.3	295.9	-21.4%	9.25

Technology Key

DCP	Cam Phaser - Dual	6AMT	6-Speed Automated Manual
CCP	Cam Phaser - Coupled	CVT	Continuously Variable Transmission
DVVL	Variable Valve Lift - Discrete	42VSS	42-Volt 10 kW ISG (Start Stop)
CVVL	Variable Valve Lift - Continuous	42VMA	42-Volt 10 kW ISG (Motor Assist)
EHVA	Camless Valve Actuation - Electrohydraulic	EPS	Electric Power Steering
TURB	Turbocharging	HIALT	Improved Alternator (Higher efficiency)
CYLDCT	Cylinder Deactivation	EWP	Electric Water Pump
GDIS	GDI Stoichiometric	EOP	Electric Oil Pump
GDILBS	GDI Lean Burn Stratified	FIXAC	Fixed Displacement AC Compressor
GHCCI	Gasoline HCCI	VARAC	Variable Displacement AC Compressor
HSDI	Diesel	MR	Mass Reduction
DAMM	Diesel – Advanced Multi-Mode		
5AT	5-Speed Automatic		
6AT	6-Speed Automatic		

Table B-23: Small Truck Technology Combination Simulation Results

Small Truck Technology Combination Simulation Results			Tier 2 Bin 5 CO_2 [g/mi]				0-60 MPH
Simulation	Technology	Displ. [l]	FTP	HWY	Comb.	Delta %	[s]
MY 02 B/L	MPFI,4AT	3.40	476.5	363.6	425.7	0.0%	9.99
Case 00	DCP,DVVL,6AT	3.20	429.3	331.9	385.5	-9.4%	9.23
Case 01	DCP,6AT	3.20	435.6	333.1	389.5	-8.5%	9.23
Case 02	DCP,TURB,6AT,EPS,HIALT	1.70	428.8	321.3	380.4	-10.6%	9.22
Case 03	DCP,CYLDCT,6AT	3.20	417.0	325.5	375.8	-11.7%	9.23
Case 04	DCP,TURB,GDIS,6AMT,EPS,HIALT	1.64	344.1	302.8	325.5	-23.5%	9.24
Case 05	CCP,DVVL,CYLDCT,6AMT,EPS,HIALT	2.96	358.1	308.6	335.8	-21.1%	9.23
Case 06	CCP,DVVL,CYLDCT,6AT,42VMA,EPS,EWP,EOP	2.91	336.9	305.2	322.6	-24.2%	9.24
Case 07	DCP,CYLDCT,GDIS,6AMT,EPS,HIALT	2.77	367.4	310.6	341.8	-19.7%	9.22
Case 08	DAMM,6AMT,EPS,HIALT	2.33	349.2	322.1	337.0	-20.8%	9.14
Case 09	HSDI,6AMT,EPS,HIALT	2.33	325.2	295.5	311.8	-26.7%	9.14
Case 10.1	CCP,DVVL,CYLDCT,6AMT,EPS,HIALT,FIXAC	2.96	447.8	356.0	406.5	-4.5%	9.23
Case 10.2	CCP,DVVL,CYLDCT,6AMT,EPS,HIALT,VARAC	2.96	398.2	331.2	368.1	-13.5%	9.23
Case 11	EHVA,GDIS,6AMT,EPS,HIALT	2.77	334.8	292.0	315.5	-25.9%	9.21

Technology Key

DCP	Cam Phaser - Dual	6AMT	6-Speed Automated Manual
CCP	Cam Phaser - Coupled	CVT	Continuously Variable Transmission
DVVL	Variable Valve Lift - Discrete	42VSS	42-Volt 10 kW ISG (Start Stop)
CVVL	Variable Valve Lift - Continuous	42VMA	42-Volt 10 kW ISG (Motor Assist)
EHVA	Camless Valve Actuation - Electrohydraulic	EPS	Electric Power Steering
TURB	Turbocharging	HIALT	Improved Alternator (Higher efficiency)
CYLDCT	Cylinder Deactivation	EWP	Electric Water Pump
GDIS	GDI Stoichiometric	EOP	Electric Oil Pump
GDILBS	GDI Lean Burn Stratified	FIXAC	Fixed Displacement AC Compressor
GHCCI	Gasoline HCCI	VARAC	Variable Displacement AC Compressor
HSDI	Diesel	MR	Mass Reduction
DAMM	Diesel – Advanced Multi-Mode		
5AT	5-Speed Automatic		
6AT	6-Speed Automatic		

Table B-24: Large Truck Technology Combination Simulation Results

Large Truck Technology Combination Simulation Results			Tier 2 Bin 5 CO_2 [g/mi]				0-60 MPH
Simulation	Technology	Displ. [l]	FTP	HWY	Comb.	Delta %	[s]
MY 02 B/L	MPFI,4AT	5.30	563.3	406.1	492.6	0.0%	8.86
Case 00	CCP,6AT	5.00	527.1	388.1	464.6	-5.7%	7.97
Case 01	CCP,DVVL,6AT	4.70	512.6	386.4	455.8	-7.5%	7.95
Case 02	DCP,CYLDCT,6AT	4.70	494.4	381.2	443.5	-10.0%	7.95
Case 03	CCP,CYLDCT,6AT	5.00	498.8	381.3	445.9	-9.5%	7.97
Case 04	CCP,DVVL,CYLDCT,6AT,EPS,HIALT	4.70	475.3	374.6	430.0	-12.7%	7.95
Case 05	CCP,DVVL,CYLDCT,6AMT,EPS,HIALT	4.80	437.0	370.8	407.2	-17.3%	8.01
Case 06	GDILBS,6AMT,EPS,HIALT	4.50	427.2	361.5	397.6	-19.3%	7.99
Case 07	CCP,6AT,-15% MR	4.20	451.3	338.6	400.6	-18.7%	7.92
Case 08	CCP,DVVL,CYLDCT,6AT,EPS,HIALT,-15% MR	3.90	405.3	325.7	369.5	-25.0%	7.93
Case 09	CCP,DVVL,CYLDCT,6AT,42VMA,EPS,EWP,EOP	4.60	405.3	366.4	387.8	-21.3%	7.97
Case 10	DAMM,6AMT,42VMA,EPS,EWP,EOP	3.30	369.4	369.9	369.6	-25.0%	7.92
Case 11	GDILBS,6AMT,42VMA,EPS,EWP,EOP	4.20	372.6	352.3	363.5	-26.2%	7.98
Case 12	EHVA,GDIS,6AMT,EPS,HIALT	4.50	419.8	357.1	391.6	-20.5%	7.96
Case 13	CCP,CYLDCT,GDIS,6AMT,EPS,HIALT	4.50	467.9	380.5	428.6	-13.0%	7.95

Technology Key

DCP	Cam Phaser - Dual	6AMT	6-Speed Automated Manual
CCP	Cam Phaser - Coupled	CVT	Continuously Variable Transmission
DVVL	Variable Valve Lift - Discrete	42VSS	42-Volt 10 kW ISG (Start Stop)
CVVL	Variable Valve Lift - Continuous	42VMA	42-Volt 10 kW ISG (Motor Assist)
EHVA	Camless Valve Actuation - Electrohydraulic	EPS	Electric Power Steering
TURB	Turbocharging	HIALT	Improved Alternator (Higher efficiency)
CYLDCT	Cylinder Deactivation	EWP	Electric Water Pump
GDIS	GDI Stoichiometric	EOP	Electric Oil Pump
GDILBS	GDI Lean Burn Stratified	FIXAC	Fixed Displacement AC Compressor
GHCCI	Gasoline HCCI	VARAC	Variable Displacement AC Compressor
HSDI	Diesel	MR	Mass Reduction
DAMM	Diesel – Advanced Multi-Mode		
5AT	5-Speed Automatic		
6AT	6-Speed Automatic		

Figure B-7: Small Car Combined CO_2 Emissions

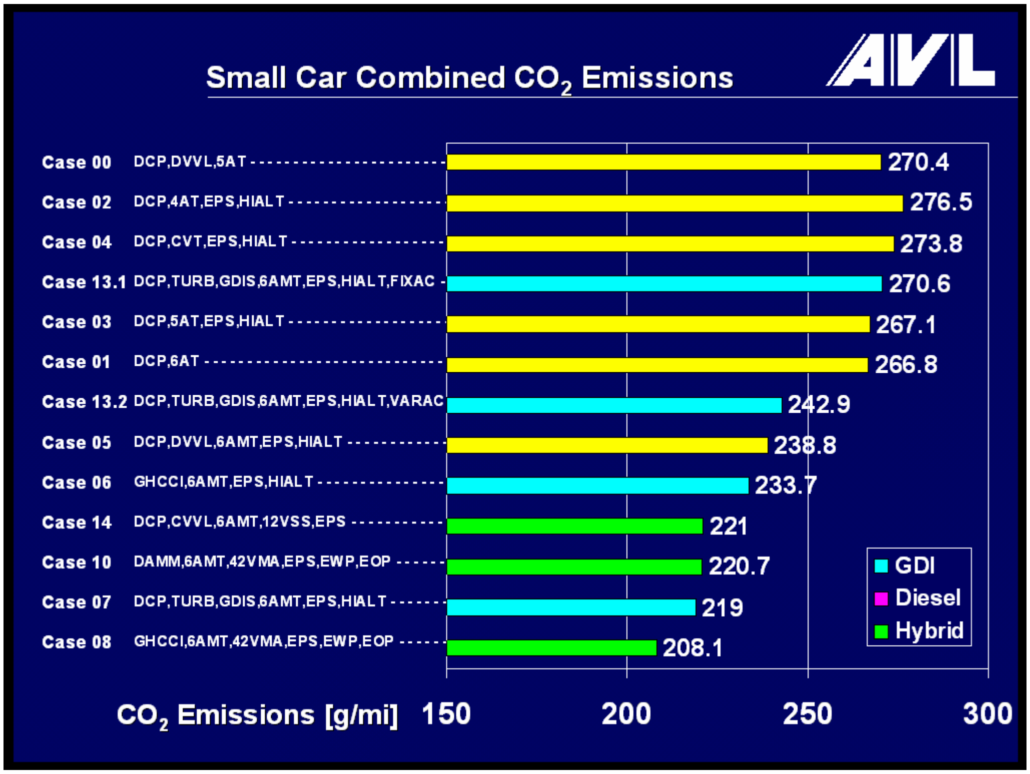


Figure B-8: Small Car Reduction in Combined CO_2 Emissions (Compared to 2002 MY Baseline)

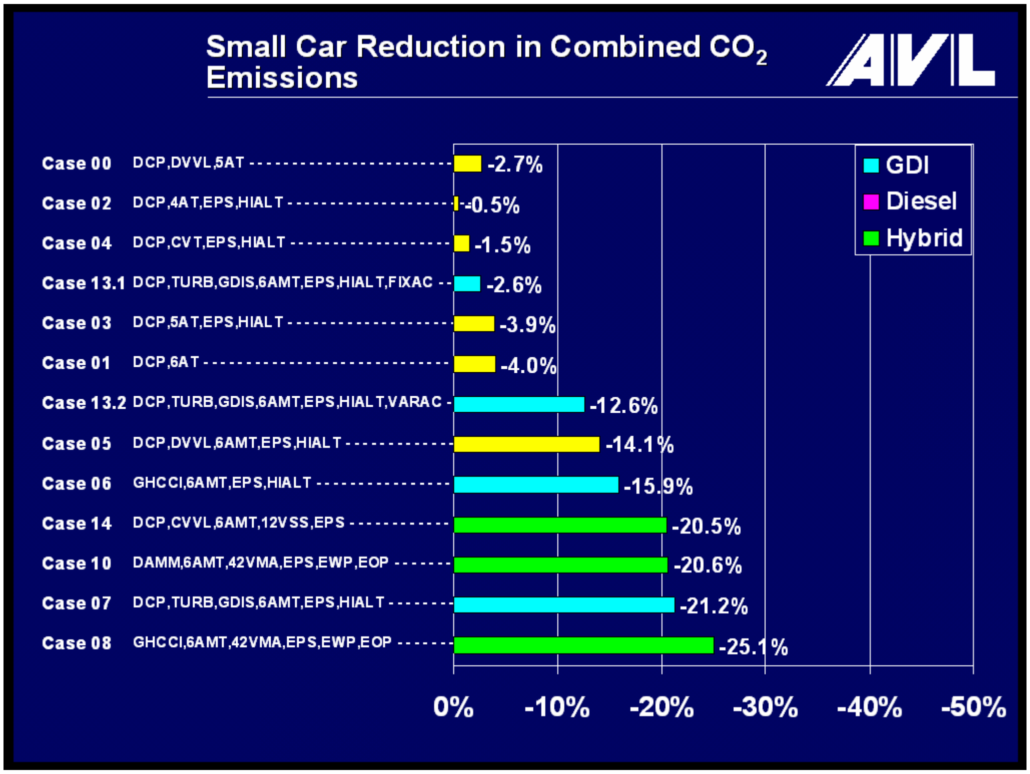


Figure B-9: Large Car Combined CO_2 Emissions

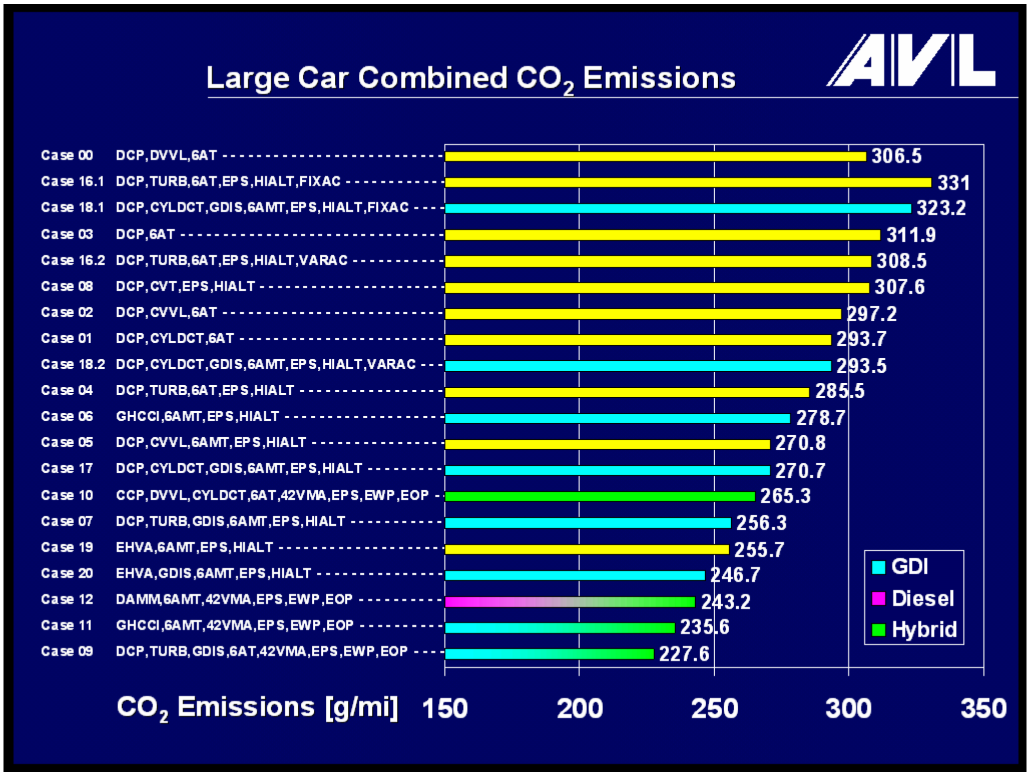


Figure B-10: Large Car Reduction in Combined CO_2 Emissions (Compared to 2002 MY Baseline)

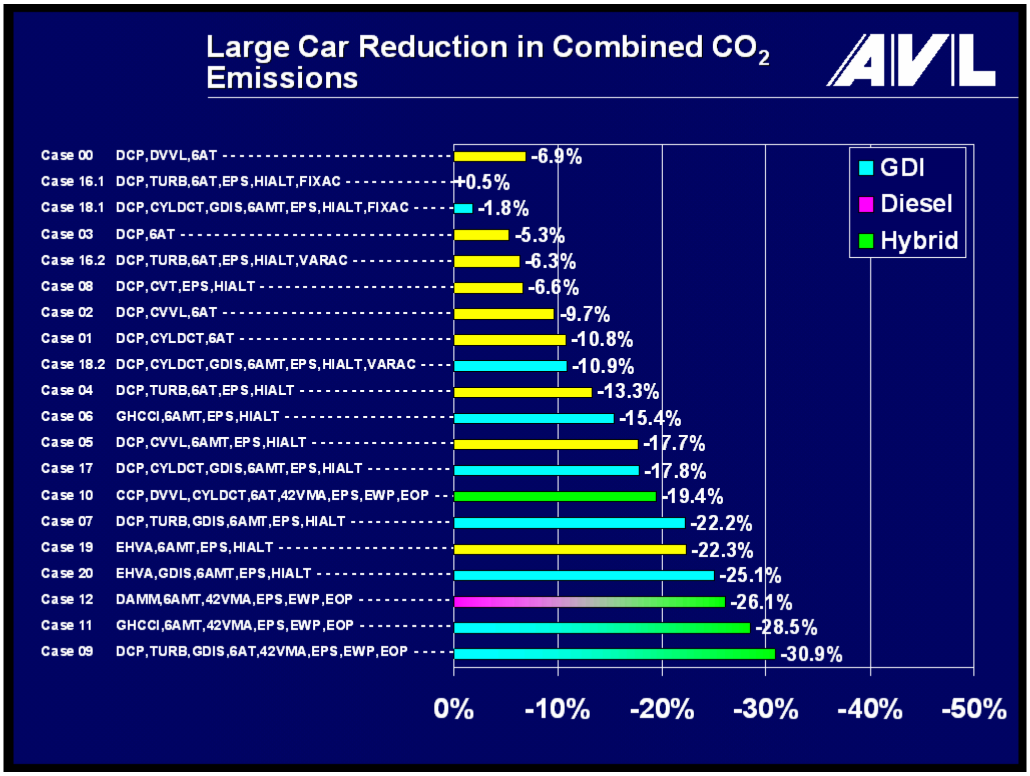


Figure B-11: Minivan Combined CO_2 Emissions

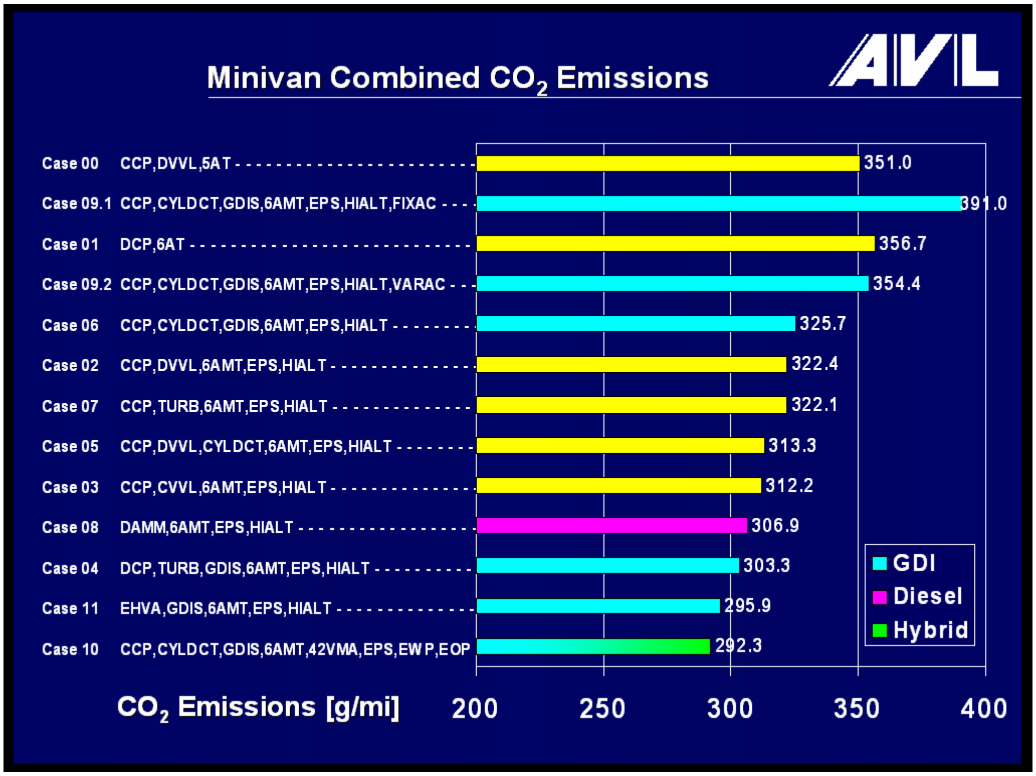


Figure B-12: Minivan Reduction in Combined CO_2 Emissions (Compared to 2002 MY Baseline)

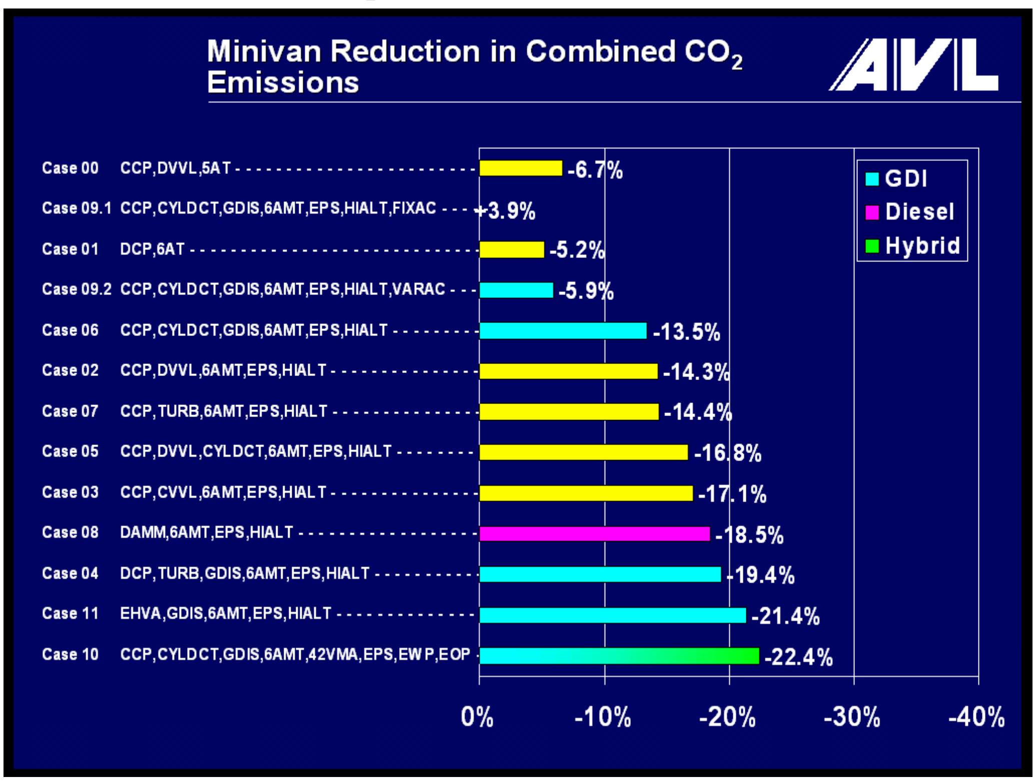


Figure B-13: Small Truck Combined CO_2 Emissions

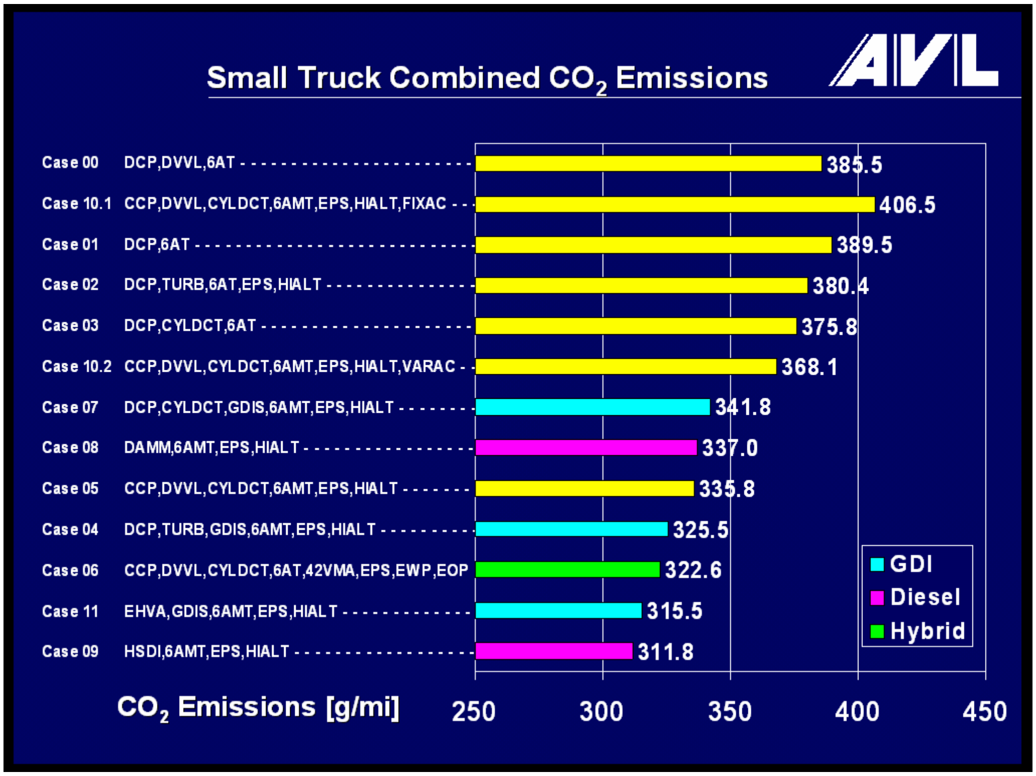


Figure B-14: Small Truck Reduction in Combined CO_2 Emissions (Compared to 2002 MY Baseline)

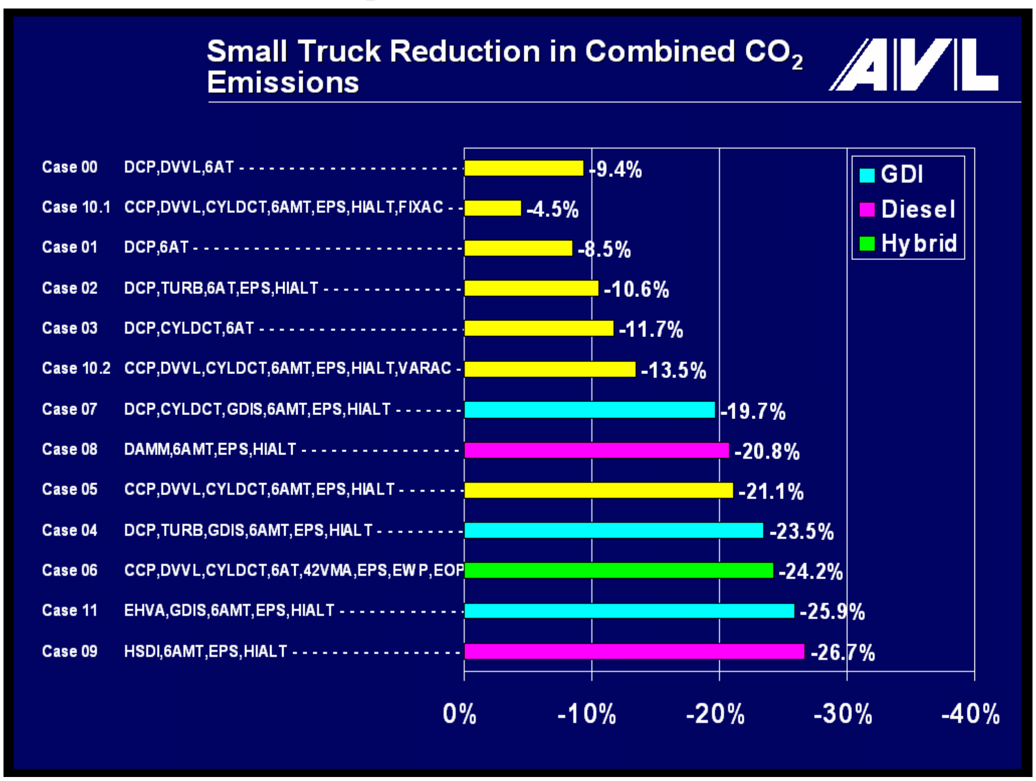


Figure B-15: Large Truck Combined CO_2 Emissions

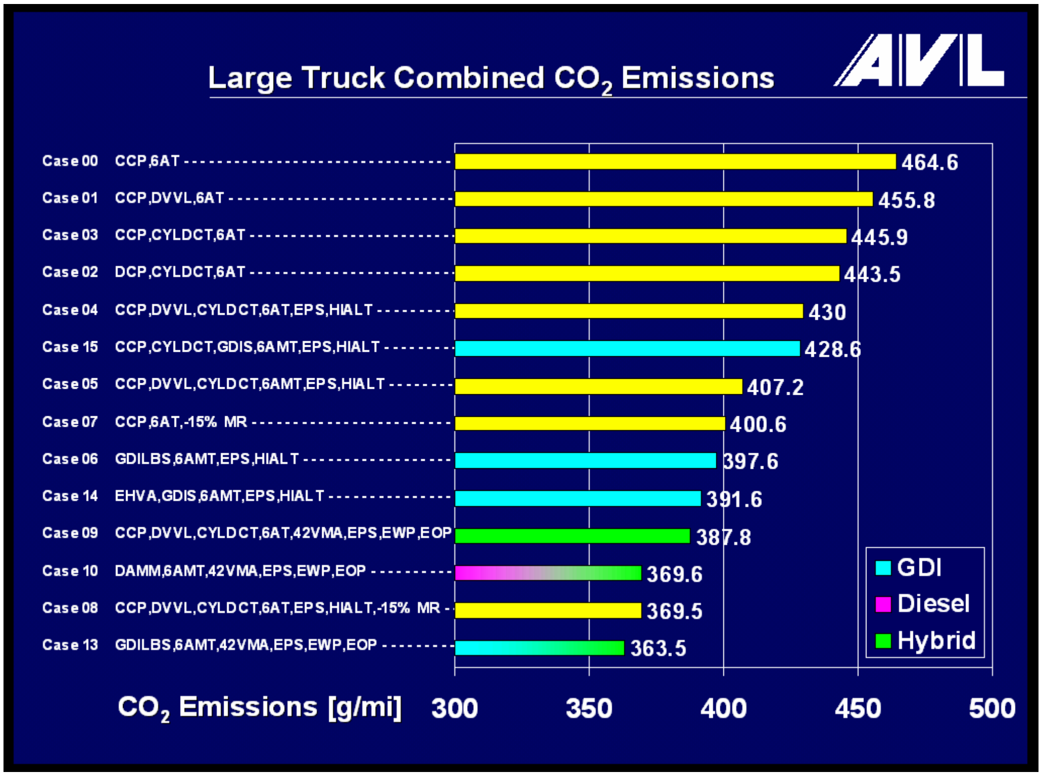
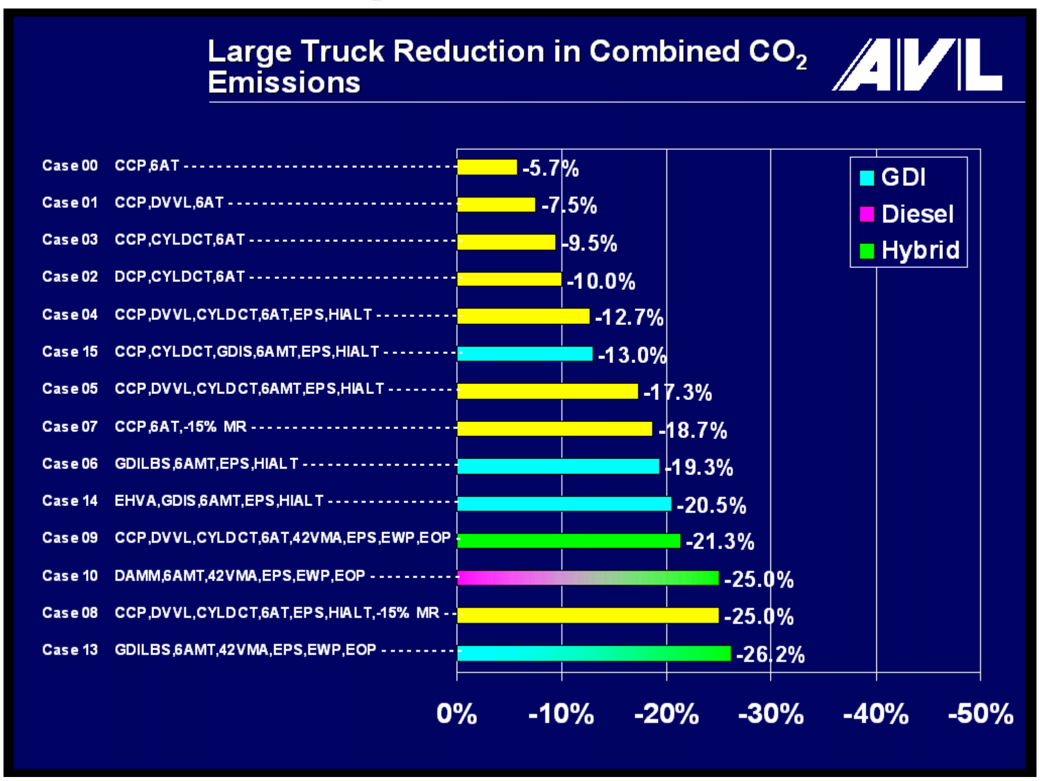


Figure B-16: Large Truck Reduction in Combined CO_2 Emissions (Compared to 2002 MY Baseline)



Appendix C: Vehicle Cost Matrix

Appendix C: Vehicle Cost Matrix

Technology	L4	V6	V6	V6	V8	Technology Description - Hardware and Functionality
	Vehicle Manufacturer Discrete Hardware Cost Delta 2009+ High Volume Variable Hardware Cost Delta Per Vehicle					
Engine Technologies						
2002 Baseline MPFI Engine 2002 Baseline Transmission	**2.2L DOHC 4V A4 FWD Cavalier (SC)**	**3.0L DOHC 4V A4 FWD Taurus (LC)**	**3.4L DOHC 4V A4 RWD Tacoma (ST)**	**3.3L OHV 2V A4 FWD Town & C (MV)**	**5.3L OHV 2V A4 AWD Sierra (LT)**	
DOHC from OHV	-	-	-	$500	$600	Substitution of DOHC 4V gas engine for OHV 2V gas engine of equal cylinder count. Content increase for Vee engine inlcudes: New cam drive, +3 camshafts, +2 valves per cylinder, cam bearing surfaces, extra valve seats and valve guides, roller cam followers. Assumes Al heads and Fe block for OHV and Al heads and Al block DOHC
External EGR Credit	($25)	($25)	($25)	($25)	($25)	External EGR can be deleted if not needed or another means of exhaust dilution is available.
Variable Cam Phaser						
· Single	$35	$70	$70	$35	$35	**Line DOHC engines** -1 phaser on intake **Vee DOHC engines** - 2 phasers (1 on each intake bank) **Line or Vee OHV** - 1 phaser provides coupled functionality
· Dual	$70	$140	$140	$140	$140	**Line DOHC engines -** 2 phasers **Vee DOHC engines** - 4 phasers Practical solution for OHV engines undefined
· Coupled	$50	$115	$115	$35	$35	**Line DOHC engines** -1 phaser linked to both camshafts **Vee DOHC engines** - 2 phasers (1 linked to both camshafts on each bank) **Line or Vee OHV** - 1 phaser provides coupled functionality
Variable Valve Lift (VVL)						Intake phasing costs must be added to all VVL and CVVL concepts.
Discrete 2-step VVL (DVVL) - Electromagnetic (EM)	$120					4 lost motion devices each operating 1 intake valve **pair** per cylinder. 4 actuators, drivers, harness. Intake valves only. Baseline DOHC valvetrain is separate cam lobe and roller finger follower w/ HLA for each valve of 4V per cylinder. Cylinder head redesign required for low cost valve pairing concept.
DVVL - EM		$180	$180			6 lost motion devices each operating 1 intake valve **pair** per cylinder. 6 actuators, drivers, harness. Intake valves only. Baseline DOHC valvetrain cost includes separate cam lobe and roller finger follower w/ HLA for each valve of 4V per cylinder. Cylinder head redesign required for low cost valve pairing concept.
DVVL - Electrohydraulic (EH)	$75					4 lost motion devices each operating 1 intake valve **pair** per cylinder. 2 solenoids, drivers, harness. Intake valves only. Baseline DOHC valvetrain is separate cam lobe and roller finger follower w/ HLA for each valve of 4V per cylinder. Cylinder head redesign required for low cost valve pairing concept.
DVVL - EH		$115	$115			6 lost motion devices each operating 1 intake valve **pair** per cylinder. 3 solenoids, drivers, harness. Intake valves only. Baseline DOHC valvetrain is separate cam lobe and roller finger follower w/ HLA for each valve of 4V per cylinder. Cylinder head redesign required for low cost valve pairing concept.
DVVL - EH				$115		6 lost motion devices each operating 1 intake valve per cylinder. 3 solenoids, drivers, harness. Intake valves only. Baseline cost is 2V per cylinder OHV using RHVL lifters.
DVVL - EH					$150	8 lost motion devices each operating 1 intake valve per cylinder. 4 solenoids, drivers, harness. Intake valves only. Baseline cost is 2V per cylinder OHV using RHVL lifters.
Continuously Variable Valve Lift (CVVL)	$150	$275	$275	$275+DOHC	$300+DOHC	Ratio linkage including roller element for each **pair** of intake valves. 1 control shaft positioned by 1 electrohydraulic actuator per bank. Forked finger follower operates 1 pair of intake valves per cylinder. Hydraulic lash adjusters remain. Control of intake valves only. DOHC engines only. Baseline DOHC valvetrain is separate cam lobe and roller finger follower w/ HLA for each valve of 4V per cylinder. Cylinder head redesign required for low cost valve pairing concept.

Technology	L4	V6	V6	V6	V8	Technology Description - Hardware and Functionality
	Vehicle Manufacturer Discrete Hardware Cost Delta 2009+ High Volume Variable Hardware Cost Delta Per Vehicle					
Cylinder Deactivation - Electrohydraulic (EH)						
Cylinder Deactivation - EH		**$115**	**$115**			6 lost motion devices each operating 1 valve **pair**. 3 solenoids, drivers, harness. Deactivating all I & E valves in each cylinder for 1/2 of the engine cylinders. Excludes any necessary NVH improvements. Baseline DOHC valvetrain is separate cam lobe and roller finger follower w/ HLA for each valve of 4V per cylinder. Cylinder head redesign required for low cost valve pairing concept.
Cylinder Deactivation - EH				**$115**		6 lost motion devices each operating 1 valve. 3 solenoids, drivers, harness. Deactivating all I & E valves in each cylinder for 1/2 of the engine cylinders. Excludes any necessary NVH improvements. Baseline cost is 2V per cylinder OHV using RHVL lifters.
Cylinder Deactivation - EH					**$150**	8 lost motion devices each operating 1 valve. 4 solenoids, drivers, harness. Deactivating all I & E valves in each cylinder for 1/2 of the engine cylinders. Excludes any necessary NVH improvements. Baseline cost is 2V per cylinder OHV using RHVL lifters.
DVVL/Deact Combinations						Intake phasing costs must be added to all VVL combinations
DVVL-EH with Cylinder Deactivation - EH	**$330**	**$200**	**$200**	**$200**	**$260**	Start with DVVL on intake valves for all cylinders. Add third step (closed) to intake valves on 1/2 the cylinders for deact - requires higher cost solenoids - 1 per deacted cylinder. Add 2-step on exhaust valves for deact on 1/2 the cylinders. Add 2-step solenoids to get to 1 per non-deact cylinder - no cylinder pairing possible. Can operate DVVL and / or Cylinder Deact independently at any time - a deactivated cylinder does not use DVVL while deactivated.
Camless Valve Actuation (CVA)						
· Electromagnetic Actuation	**$690**	**$780**	**$780**	**$1,100**	**$1,300**	Electromagnetic camless valve actuation. Assume 4 valves per cylinder. Includes control electronics. Expressed as net cost per engine.1 actuator per valve **pair**. Controller. Credit existing valvetrain. 42V is a requirement - these costs are excluded
· Electrohydraulic Actuation	**$575**	**$650**	**$650**	**$900**	**$1,100**	Electrohydraulic camless valve actuation. Assume 4 valves per cylinder. 1 actuator per valve **pair**. Includes hydraulics and control electronics. Expressed as net cost per engine.
Variable Geometry Turbocharging	**$400**	**$400**	**$400**	**$400**	**$400**	VGT gasoline turbo, charge air cooler, piston upgrade, piston cooling, steel crankshaft, cooling system upsize, plumbing, rings, pressure sensor & bearing upgrade. Excludes any needed increase in transmission torque capacity or modifications to aftertreatment system.
Electric Assist Turbocharging	**$475**	**$475**	**$475**	**$475**	**$475**	Waste-gate gasoline turbo with 12V EAT functionality at 800-1500W consumption. Includes charge air cooler, piston and ring upgrade, piston cooling, steel crankshaft, cooling system upsize, plumbing, head gasket upgrade, pressure sensor & bearing upgrade. Excludes any needed increase in transmission torque capacity or modifications to aftertreatment system.
Gasoline Engine Downsizing Credits						These credits apply only when the baseline vehicle gasoline engine is replaced by another gasoline engine of the type described for each credit. For the study AVL and NESCCAF modeled/scaled turbo gas engines at 65%, aggressive hybrids at 63% and moderate hybrids at 74% so these credits can be applied to those vehicle packages.
Downsizing credit (for both VGT and EAT)	**na**					L4 DOHC 4V remains L4 DOHC 4V
Downsizing credit (for both VGT and EAT)		($700)				V6 DOHC 4V moves to L4 DOHC 4V
Downsizing credit (for both VGT and EAT)		($550)				V6 DOHC 4V moves to L5 DOHC 4V
Downsizing credit (for both VGT and EAT)			($700)			V6 DOHC 4V moves to L4 DOHC 4V
Downsizing credit (for both VGT and EAT)			($550)			V6 DOHC 4V moves to L5 DOHC 4V
Downsizing credit (for both VGT and EAT)				($200)		V6 OHV 2V moves to L4 DOHC 4V
Downsizing credit (for both VGT and EAT)				($50)		V6 OHV 2V moves to L5 DOHC 4V
Downsizing credit (for both VGT and EAT)					($300)	V8 OHV 2V moves to L6 DOHC 4V
Supercharging	**$435**	**$435**	**$435**	**$435**	**$435**	Advanced supercharger including charge air cooler, piston and ring upgrade, piston cooling, steel crankshaft, bypass and plumbing, head gasket upgrade, pressure sensor & bearing upgrade. Excludes any needed increase in transmission torque capacity.
Variable Charge Motion	**$30**	**$50**	**$50**	**$50**	**$60**	Active intake port tuning utilizing hydraulically actuated "bumps" in each port
Direct Injection (DIG) - Stoichiometric	**$135**	**$185**	**$185**	**$185**	**$210**	Wall-guide DIG 90-100 bar pressures. Excludes all modifications to base engine
Direct Injection (DIG) - Lean Burn Stratified Charge	**$135**	**$185**	**$185**	**$185**	**$210**	Wall-guide DIG 90-100 bar pressures. Excludes all modifications to base engine
Lean Burn DIG Aftertreatment Cost Delta	**$385**	**$500**	**$570**	**$560**	**$900**	AVL designed 3.0L V6 with 3.73 g/mi engine-out NOx. System includes inactive exhaust cooler. Scaled using baseline engine
Gasoline HCCI (AVL CSI System)	**$400**	**$600**	**$600**	**na**	**na**	AVL CSI System: Wall-guide DIG 90-100 bar, ion sense or virtual cylinder pressure sensing, intake phaser, DVVL-EH, supplemental EH exhaust valve operation for dilution management w/ high pressure oil pump and plumbing. Stoichiometric aftertreatment.

Technology	Vehicle Manufacturer Discrete Hardware Cost Delta 2009+ High Volume Variable Hardware Cost Delta Per Vehicle L4	V6	V6	V6	V8	Technology Description - Hardware and Functionality
Baseline high-speed Diesel Engine Displacement	**1.78L L4**	**2.40L L4**	**2.28L L4**	**2.31L L4**	**3.85L L6**	Downsized DOHC 4V turbo diesel engines modeled by AVL to provide equivalent performance to each baseline gas engine.
Baseline high-speed Diesel	**$1,000**	**$300**	**$300**	**$800**	**$950**	DOHC 4V turbo diesel: Common rail, ~1,800 bar, Piezo-actuated injectors, VNT, cooled EGR. Includes downsizing credit. Excludes any needed increase in transmission torque capacity.
Baseline diesel aftertreatment Cost Delta over stoich.	**$500**	**$575**	**$600**	**$600**	**$1,000**	AVL designed 2-leg system revised to single leg per MECA. Scaled from 2.8L V6 with 0.32 g/mi engine-out NOx.
Diesel Advanced Multi-Mode	**$1,000**	**#REF!**	**#REF!**	**#REF!**	**#REF!**	DOHC 4V turbo diesel: Common rail, ~1,800 bar, Piezo-actuated injectors, VNT, cooled EGR. Includes downsizing credit. Excludes any needed increase in transmission torque capacity.
Diesel Advanced Multi-Mode Aftertreatment Cost Delta	**$250-350**	**$300-450**	**$280-400**	**$285-400**	**$500-725**	FEV-NREL APBF-DEC light duty advanced aftertreatment system (DEER 8-2003). Scaled from 1.9L engine containing 1 pre-cat (DOC + LNT functionality), 1 underfloor LNT and CDPF. MECA supplied PGM loadings expressed as a range.
Diesel Engine and Aftertreatment downsizing substituion for Aggressive Hybrid					**$900**	Per NESCCAF design scaling of hybrid vehicles, use L4 DOHC 4V turbo diesel AMM for this large truck vehicle class but only with the aggressive hybrid drivetrain. Aftertreatment cost is included in this cost.
Variable Compression Ratio	**$320**	**$380**	**$380**	**$380**	**$440**	Hydraulic pump, acutators, tilt design, can move CR from 7-10.
Drivetrain Technologies						
5-Speed Automatic Transmission	**$100**	**$100**	**$100**	**$100**	**$100**	Conventional step gear
6-Speed Automatic Transmission	**$50**	**$75**	**$75**	**$75**	**$80**	Lepelletier gear set design
Continuously Variable Transmission (CVT)	**$150**	**$175**	**$175**	**$175**	**na**	Belt CVT. NESCCAF assumptions: Assumes competitive market for belt technology free of licenses and IP protection. Assumes global volume and capital infrastructure on par with step-gear transmissions.
Automated Manual Transmission 6 speed	**neutral**	**neutral**	**neutral**	**neutral**	**neutral**	6-speed, dual wet clutch, fully automated. Piece cost only - i.e., US manual transmission capacity does not exist vs. Europe
12V belt starter-alternator (idle off)	**$200**	**na**	**na**	**na**	**na**	2kW machine. Includes inverter/controller, cable upgrade, belt tensioner upgrade. Credit alternator. Starter motor required for cold start. Maximim cylinder displacement ~ .45L for warm re-start. Includes 12V Pb acid battery upgrade.
42 Volt BAS - Belt Drive w/ Launch, Regen, Idle Off	**$450**	**$450**	**$450**	**$450**	**$500**	4kW machine. Includes belt upgrade, power electronics, DC-DC converter for split system. Liquid cooled electronics. Credit alternator and starter. Maintain starter motor for 5.3L cold crank. Excludes battery upgrade.
42 Volt FAS w/ Launch, Regen, Idle Off	**$800**	**$800**	**$800**	**$800**	**$800**	10kW motor, flywheel integration, power electronics, DC-DC converter split sytem, liquid cooled, credit starter and alternator. Excludes battery upgrade.
42V system lead acid battery for BAS	**$120**	**$120**	**$120**	**$120**	**$120**	36V 20Ah advanced adsorbent glass mat (AGM) lead acid battery - .72 KwHr. Targeted primarily for the BAS system above.
42V system lead acid battery set for FAS	**$330**	**$330**	**$330**	**$330**	**$330**	36V 55Ah advanced adsorbent glass mat (AGM) lead acid battery set - 1.98 KwHr. Targeted primarily for the FAS system above.
42V system NiMH battery upgrade	**$400**	**$400**	**$400**	**$400**	**$400**	Full battery pack including 36 cells, 43.2V, 14A-h, .605 KwHr capacity, 2117 kJ energy (Ref: SAFT Vh10/42, air cooled (40C) 36XVH4/5SF) for BAS or FAS
42V system NiMH battery upgrade	**$1,090**	**$1,090**	**$1,090**	**$1,090**	**$1,090**	Full battery pack including 36 cells, 43.2V, 45.8 A-h, 1.98 KwHr capacity for FAS
Moderate Hybrid - Motor Assist						04 Honda Civic Hybrid architecture scaled by NESCCAF to fit each vehicle class. Net cost includes a conventional transmission, NiMH battery pack at 144V, control and power electronics including 1 inverter for 144V system, 1 permanent magnet motor/generator. Credit given for baseline vehicle generator. **Excludes cost of replacement battery pack.**
	$1,650					Battery pack 9.0 Ah, mogen 15 Kw, CVT transmission
		$2,100		**$2,100**		Battery pack 12.0 Ah, mogen 20 Kw, CVT transmission
			$2,100			Battery pack 12.0 Ah, mogen 20 Kw, CVT transmission. This vehicle may not meet the load carrying and towing continuous gradeability performance of the baseline vehicle for this class.
					$2,400	Battery pack 15.0 Ah, mogen 25 Kw, 6 speed automatic transmission. This vehicle may not meet the load carrying and towing continuous gradeability performance of the baseline vehicle for this class.

Technology	Vehicle Manufacturer Discrete Hardware Cost Delta 2009+ High Volume Variable Hardware Cost Delta Per Vehicle L4	V6	V6	V6	V8	Technology Description - Hardware and Functionality
Aggressive Hybrid - Fully Integrated						04 Toyota Prius hybrid architecture design scaled by NESCCAF to fit each vehicle class. Net cost includes continuously variable hybrid transmission, NiMH battery pack at 201.6V, control and power electronics including 2 inverters w/ 1 dc:dc converter for 500V system voltage, 1 permanent magnet generator/engine starter, 1 permanent magnet drive motor. Credit given for baseline vehicle generator and starter motor. **Excludes cost of any replacement battery pack.**
	$2,500					Battery pack 5.9Ah, drive motor 45Kw, generator 25Kw
		$3,100		**$3,100**		Battery pack 7.8Ah, drive motor 60Kw, generator 30Kw
			$3,100			Battery pack 7.8Ah, drive motor 60Kw, generator 30Kw. This vehicle may not meet the load carrying and towing continuous gradeability performance of the baseline vehicle for this class.
					$4,000	Battery pack 10.4Ah, drive motor 80Kw, generator 40Kw. This vehicle may not meet the load carrying and towing continuous gradeability performance of the baseline vehicle for this class.
Other Load Reducing Technologies						
Advanced Power Steering						
· Electrohydraulic power steering (EHPS)					**$60**	If 14V electrical system, EHPS required for large truck case
· Electric power steering (EPS)	**$20**	**$40**	**$40**	**$40**	**$40**	14/42V EPS. 42V is requirement for large truck case EPS.
Electric 42V Demand Water Pump	**$50**	**$50**	**$50**	**$50**	**$50**	42V requirement for demand water pump.
High Efficiency Generator	**$40**	**$40**	**$40**	**$40**	**$40**	80% high efficiency Lundell machine
Weight Reduction	**$3**	**$3**	**$3**	**$3**	**$3**	Aluminum intensive vehicle - body. Cost per pound saved.

Important Notes on Technology Cost Matrix

Vehicle manufacturer costs represent variable hardware cost delta over baseline technologies. R&D, capital investment and other costs associated with implementing new technologies are excluded.
Costs are forecast 2009+ at assumed high volume levels. See Methodology Section for full description.

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References for Appendix C

As mentioned previously in this report, the costs listed in Appendix C were developed by the Martec Group, Inc. from a literature review and from field interviews conducted with individuals representing all aspects of the automotive industry, including the management, engineering, purchasing, finance, planning and product management divisions of both manufacturers and parts suppliers. Wherever possible, information gleaned from technical papers was verified in interviews. A partial list of sources used for the study is presented below.

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Appendix D: Vehicle Air Conditioning

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Vehicle air conditioning (A/C) systems impact vehicular GHG emissions through three distinct mechanisms. Two mechanisms impact vehicle tailpipe emissions of CO_2, while the third mechanism is emissions (refrigerant leakage) from the A/C system itself. The increased vehicle tailpipe emissions are generally referred to as "*indirect emissions*" since they do not emanate directly from the A/C system. Leakage-related emissions are generally referred to as "*direct emissions*" since they are released directly by the A/C system.

Indirect emissions result from two influences. First, when operating, A/C systems place an additional load on the vehicle engine, increasing vehicle CO_2 emissions. Second, regardless of operational status, A/C system mass must be transported whenever a vehicle is moved, and this also places an additional load on the vehicle engine (relative to an otherwise identical vehicle without A/C), increasing vehicle CO_2 emissions. A typical A/C system weighs on the order of 30-35 pounds. [1]

A/C systems function by transferring heat through a working fluid, which is commonly known as the system refrigerant. Current vehicle A/C systems utilize HFC-134a (1,1,1,2-tetrafluoroethane; $C_2F_4H_2$) as the working refrigerant. HFC-134a has a global warming potential (GWP) 1300 times that of CO_2. [2] Accordingly, any refrigerant that leaks from the A/C system represents a potent source of GHG emissions.

This study evaluated all three sources of A/C-related GHG emissions. Both direct and indirect emissions were assessed through a stand-alone analytical assessment. To validate the analytical assessment, indirect A/C operational emissions were also assessed through application of the AVL CRUISE simulation model.

D.1. Stand-Alone Assessment

The stand-alone assessment of vehicle A/C GHG emissions relied on the large body of A/C system evaluation test data that is currently available in the public domain. Although a diverse set of resources was utilized in the assessment, primary references are as follows:

- Direct Emissions:

  Schwarz, W., Őko-Recherche GmbH, "*Emission of Refrigerant R-134a from Mobile Air-Conditioning Systems, Annual Rate of Emission from Passenger-Car Air-Conditioning Systems up to Seven Years Old*," 360 09 006, prepared for the German Federal Environment Office, September 2001. [3]

  Schwarz, W. et al., Őko-Recherche GmbH, "*Establishing the Leakage Rates of Mobile Air-Conditioners*," B4-3040/2002/337136/MAR/C1, prepared for the European Commission (DG Environment), April 17, 2003. [4]

- Indirect Emissions:

    Forrest, W.O., Delphi, "*Air Conditioning and Gas Guzzler Tax Credits*," 2002-01-1958, Society of Automotive Engineers, Inc., 2002. [5]

    Forrest, W.O. and Bhatti, M.S., Delphi Harrison Thermal Systems, "*Energy Efficient Automotive Air Conditioning System*," 2002-01-0229, Society of Automotive Engineers, Inc., 2002. [6]

    Johnson, V.H., National Renewable Energy Laboratory, "*Fuel Used for Vehicle Air Conditioning: A State-by-State Thermal Comfort-Based Approach*," 2002-01-1957, Society of Automotive Engineers, Inc., 2002. [7]

Direct A/C System Emissions: A/C systems are designed to be closed for the life of a vehicle. Nevertheless, refrigerant emissions (i.e., leakage) can occur through several mechanisms. Small, but continuous refrigerant emissions occur through "*regular*" leakage at component joints and the compressor shaft seal, as well as through hose permeation. "*Irregular*" leakage can also occur as the result of system damage through accidents, etc. The evacuation of refrigerant either during A/C system or other vehicle service can also lead to significant or minor leakage depending on the use and efficiency of refrigerant recycling equipment. Finally, evacuation of refrigerant at the end of vehicle life also results in leakage at a rate that is also dependent on the use and efficiency of refrigerant recycling equipment.

Estimates of the rate of regular HFC-134a leakage span a relatively wide range of 10-130 grams per year, but most estimates are in the 50-60 gram per year range. [3,5,8-12] In the most detailed assessment of regular A/C system emissions, measurements of vehicle A/C system refrigerant mass were taken for 276 light duty vehicles in the European Union (EU) between November 2002 and January 2003. By comparing measured charge mass to initial fill specifications, a regular HFC-134a leakage rate of 52 grams per year was estimated. In recognition of the continuing primacy of the EU data, the stand-alone assessment assumed a regular leakage rate for current HFC-134a systems of 50 grams per year.

By definition, precise estimates of the rate of irregular HFC-134a leakage are difficult to develop. Various researchers have estimated per vehicle-equivalent irregular emission rates of 7-14 grams per year. [3,10,13] The most robust source of irregular emission rate data is also an EU-sponsored study that examined vehicle repair records from nine German service garages. By comparing A/C system losses for vehicles subject to repair to the number of (A/C equipped) customers at each study service garage, a nominal irregular emission rate of 14 grams per A/C-equipped vehicle per year was estimated.

In addition to regular and irregular leakage, refrigerant emissions also occur during system service due to imperfect recycling techniques. A loss of 4-13 percent of total system charge is generally estimated as appropriate for current recycling systems and techniques. [8,10,11,13] Losses for service facilities employing good recycling techniques appear to be on the low end of the range, at approximately 6 percent. Assuming an average initial charge of 750 grams and a normal leakage rate of 50 grams per year, vehicles will generally require A/C system service twice during their lifetime. At a 6 percent loss rate, this equates to about 45 grams per service or 90 grams per lifetime.

Similarly, imperfect recovery at the end of a vehicle's life also contributes to refrigerant emissions. A loss of 10-30 percent of remaining charge has been assumed to be reflective of such emissions, given current recycling systems and techniques. [10,11,13] Losses given good recycling techniques appear to be on the low end of the range at approximately 15 percent. Assuming an average initial charge of 750 grams, a normal leakage rate of 50 grams per year, and two years normal leakage since the last system service, vehicles will generally have about 650 grams of refrigerant remaining in the A/C system at the end of their life. At a 15 percent loss rate, this equates to about 98 grams per vehicle per lifetime.

These assumed service and end-of-life loss rates are based on good recycling and recovery practices. To the extent that actual practice is either non-existent (i.e., direct atmospheric venting) or poorly performed, refrigerant emissions will be substantially higher. For example, losses associated with atmospheric venting during two service trips during a vehicle lifetime and one end-of-life loss might be 2,500 grams of refrigerant or more. Obviously, this is a significant increase over the 188 grams (90 grams during service plus 98 grams at end-of-life) assumed in this assessment. Appropriate regulations (in place) and enforcement are, therefore, required to ensure that actual emissions approach those assumed.

Direct A/C system GHG emissions can be reduced by minimizing refrigerant leakage or by utilizing a refrigerant with a lower GWP. The EU has proposed regulations that require regular emission rates for HFC-134a systems to be controlled to 20-40 grams per year beginning in 2005, and phase-out the use of refrigerant with a GWP greater than 150 between 2009 and 2018. Since, as described above, HFC-134a has a GWP of 1300, the EU rules effectively ban the introduction of new HFC-134a A/C systems after 2018.[39] Table D-1 presents a list of alternative refrigerants that are being considered for vehicle application. As indicated, alternative refrigerants generally span three GWP ranges. HFC-152a is a hydrofluorocarbon refrigerant with half the fluorine of HFC-134a, and a GWP that is 91 percent lower. Hydrocarbons such as propane are also effective refrigerants, and their associated GWP is about 98 percent lower than HFC-134a, and 80

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[39]It is important to recognize that subsequent to the completion of the A/C system assessments described in this report, the European Parliament substantially amended the proposed EU regulations. While these amendments are subject to continuing revision during member state negotiations, they significantly alter the implications of the EU requirements. First, the amendments reduce the allowable GWP of mobile A/C systems to 50 beginning in 2011 and require the complete elimination of systems with a GWP above 50 by 2014. This would effectively prohibit both HFC-134a *and HFC-152a*, leaving CO_2 and hydrocarbons as the most likely long term A/C refrigerants in the EU. Second, the amendments eliminate the specified maximum A/C system refrigerant leakage rates of 20 and 40 grams per year scheduled to begin in 2005 and impose instead a requirement for an unspecified maximum leakage rate for A/C systems with a GWP greater than 150 beginning in 2007. The specific maximum leakage rate and associated test procedure are to be developed. So, while the amendments somewhat relax near term requirements, longer term requirements were made more stringent.

percent lower than HFC-152a. Finally, CO_2 systems represent a practical lower limit with a GWP of unity (by definition).

In this assessment, direct refrigerant emissions were investigated for six alternative vehicle A/C systems: current HFC-134a, two levels of enhanced (i.e., reduced leakage) HFC-134a, HFC-152a, propane, and CO_2. Enhanced HFC-134a systems are based on the proposed EU levels of refrigerant leakage of 40 and 20 grams per year, which reflect regular leakage reductions of about 20 and 60 percent relative to current HFC-134a systems. All alternatives except CO_2 assume an *effective* refrigerant recovery and recycling program in both the service and end-of-life industries. The absence of such a program will lead to emission rates considerably larger than those assumed in this evaluation. The CO_2 system evaluation included one practical assessment of a system with a leakage rate controlled to 50 grams per year and one "impractical" assessment of a system with annual leakage equivalent to a complete system charge. The "impractical" system assessment is intended solely to illustrate the insensitivity of overall CO_2 system GHG emission rates to refrigerant leakage assumptions - it is not intended to represent a viable market system.

Table D-1: Basic Environmental Characteristics of Selected Refrigerants [2,8,14]

Refrigerant	Compound Name	Formula	ODP[a]	GWP[b]
CFC-12	Dichlorodifluoromethane	$C(Cl)_2F_2$	1	8500
HFC-134a	1,1,1,2-Tetrafluoroethane	$C_2F_4H_2$	0	1300
HFC-152a	1,1-Difluoroethane	$C_2F_2H_4$	0	120
HC-290	Propane	C_3H_8	0	20
R-744	Carbon Dioxide	CO_2	0	1

[a] ODP is "Ozone Depletion Potential" as defined by the U.S. Environmental Protection Agency in 40 CFR Part 82. The ODP scale is based on CFC-11 (trichlorofluoromethane, $C(Cl)_3F$) so that the indicated ODP of a compound is defined as the ratio of its impact on ozone to the impact of the same mass of CFC-11.

[b] GWP is "Global Warming Potential" as defined by the U.S. Environmental Protection Agency in 40 CFR Part 82. The GWP scale is based on CO_2 (carbon dioxide) so that the indicated GWP of a compound is defined as the ratio of its impact on global warming to the impact of the same mass of CO_2.

Indirect Mass-Based A/C Emissions: Increased vehicle tailpipe CO_2 emissions due to the mass of A/C systems was estimated through an engineering assessment of the energy required to move mass. Using fundamental physical relations, it is possible to estimate the *incremental* CO_2 emitted for a given *incremental* change in vehicle mass (i.e., that due to the presence of the A/C system). This rate of change is estimated to be about 111 pounds of CO_2 per 100 pounds per 10,000 miles. Given this relationship and the associated mass of various A/C system alternatives, incremental tailpipe CO_2 emissions can be estimated.

Current A/C system mass is on the order of 30-35 pounds. For this assessment, a value of 33 pounds was assumed. Based on data for current evaluation systems, CO_2 A/C systems were assumed to have an additional one pound mass. [1] This differential is considerably less than differentials estimated by other researchers, but is based on actual component masses for a baseline HFC-134a system and its CO_2 equivalent. Empirical mass information for comparable A/C systems using other refrigerants is limited, but theoretical calculations by previous researchers have estimated that enhanced HFC-134a, HFC-152a, and hydrocarbon refrigerants would allow mass reductions of about 8 percent relative to current systems. [8]

Due to potential safety issues, HFC-152a, hydrocarbon, and CO_2 systems could require measures not currently needed on current HFC-134a systems. These measures could include active safety systems such as automatic vehicle cabin ventilation and A/C system evacuation or physical separation of the A/C system refrigerant from the vehicle cabin through the use of secondary A/C system cooling loops. If utilized, secondary loop systems may increase overall system mass, but empirical data is limited. However, given that secondary loop systems would consist of all of the components of the base system, *plus* an additional heat exchanger, a small pump to move coolant through the secondary loop, the secondary loop plumbing, the secondary loop coolant, and a secondary loop coolant reservoir, it seems likely that overall system mass will increase significantly. Based on the weight of current vehicle pumps, current system heat exchangers, current coolant lines, and the secondary coolant itself, a total secondary loop mass penalty of 8 to 9 pounds, or a mass increase of about 25 percent relative to current single loop systems seems likely.[40]

Indirect Energy-Based A/C Impacts: In addition to the indirect GHG impacts associated with A/C system mass, indirect GHG emission impacts also accrue during A/C system operation due to the energy demands of the system compressor and cabin fan. Since A/C system usage varies with climate, it is not possible to quantify an operational GHG impact that applies to all areas. Areas with significant cooling demands will promote higher indirect GHG emissions. Areas with low cooling demands may have overall A/C-related GHG impacts that only modestly exceed those associated with direct

[40] It should be noted that subsequent to the completion of the A/C portion of this study, the details of the various A/C systems included in the SAE Alternate Refrigerant Cooperative Research Program (ARCRP) were released. The ARCRP was initiated by the Society of Automotive Engineers (SAE) to evaluate the energy efficiency of various mobile A/C systems. As tested in the ARCRP, the mass differential between a comparable enhanced HFC-134a and CO_2 system was indicated to be about 8 pounds, substantially greater than that assumed in this study. However, both the HFC-134a and CO_2 systems had masses less than assumed in this study, at about 24 pounds for HFC-134a (versus 30 in this study) and 32 pounds for CO_2 (versus 34 in this study). Additionally, the ARCRP included a secondary loop system, with an incremental mass estimated to be about 17 pounds (versus 8 in this study). If A/C mass-based emissions are recalculated using these estimates, overall A/C system emissions, as presented in Table D-4 below, would be reduced at average A/C operating conditions by about 2 percent for HFC-134a, non-secondary loop HFC-152a, and non-secondary loop propane systems, while emissions for a non-secondary loop CO_2 system would be reduced by about 1 percent. Under the same operating conditions, emissions from secondary loop HFC-152a and secondary loop propane systems would increase by about 1 percent under average A/C operating conditions, while secondary loop CO_2 emissions would increase by about 2 percent. Changes would be proportionally larger under low average operating conditions and proportionally smaller under high average operating conditions. Since the author of this study has not had an opportunity to critically review the systems included in the ARCRP, it is not possible to more fully evaluate the mass differentials associated with the ARCRP data. Regardless, these data certainly are as valid as any other published data reviewed for this study and should be considered accordingly.

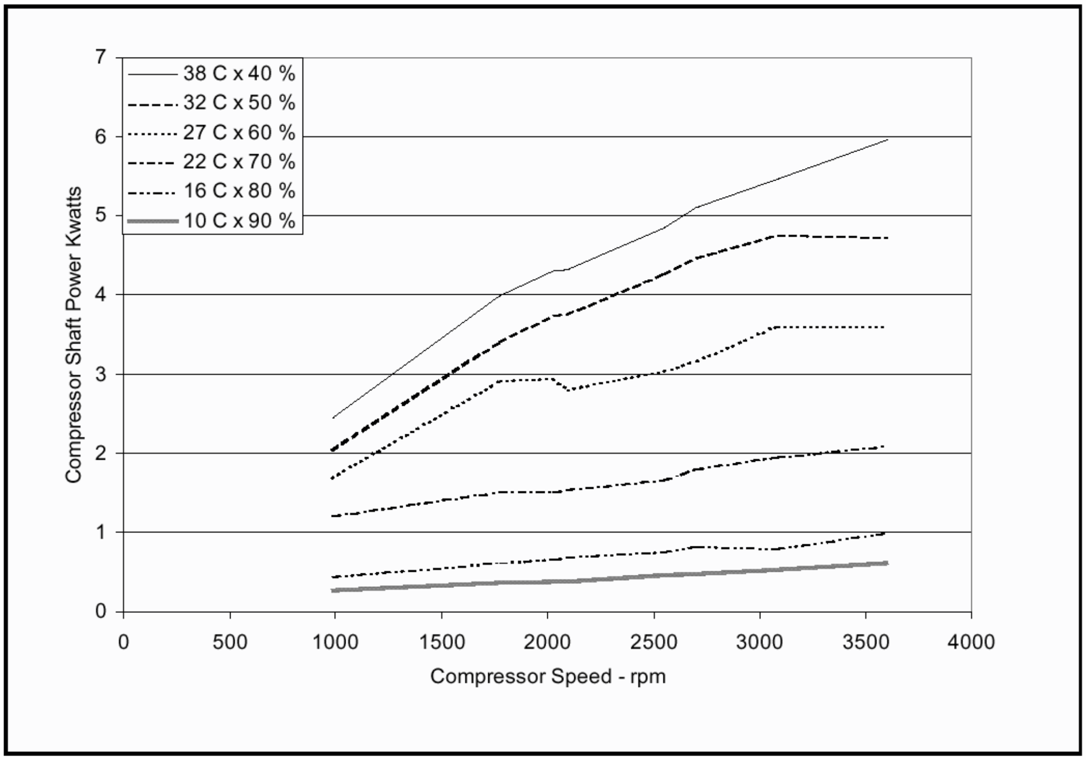
and indirect mass-based emissions. Thus, indirect operational impacts must be viewed as a range across specific geographic areas.

Indirect operational emissions can be reduced in two principal ways, through component design and through the use of alternative refrigerants. Most current vehicle A/C systems in the U.S. rely on pneumatically (freeze point) controlled fixed displacement compressors (FDCs) that provide a constant flow of refrigerant for any given demand. System control is generally limited to cycling the compressor on and off to maintain evaporator surface temperature above the point at which condensed water from the ambient air would freeze and inhibit system performance. The resulting inability to continuously adjust refrigerant flow to meet cooling demand is relatively inefficient. Alternative system designs are available and can be used to promote increased A/C efficiency. For example, externally controlled variable displacement compressors (VDCs) can be utilized to provide a dynamic system response, allowing the flow of refrigerant to be varied continuously in accordance with cooling demand. This can result in a significant efficiency improvement for most cooling demands. It is important to note that similar efficiency gains may also be possible through the incorporation of external controls in FDC systems. Such control could rely on rapid clutch cycling to provide the dynamic system response currently lacking from most A/C designs. It is not the intent of this study to specify a particular technology path to be employed by any or all manufacturers, but rather to illustrate the potential efficiency improvements that are possible through system redesign. Therefore, while this study bases its conclusions on a system utilizing an externally controlled VDC, it should not be assumed that all solutions providing similar efficiency improvement will rely on this same technology. Efficiency gains can also be achieved through the use of improved heat exchangers, the addition of suction line heat exchangers, and the incorporation of enhanced air management strategies. Through such technologies, the overall efficiency of HFC-134a systems can be improved through system redesign, without any alteration of the system refrigerant. The replacement of HFC-134a with an alternative refrigerant is a second area of potential operational efficiency improvement. To the extent that alternative refrigerant systems are more or less efficient than HFC-134a systems, overall system efficiency for a given cooling demand will be affected accordingly.

As stated above, an appropriate set of evaluation conditions must first be defined in order to estimate the operational impacts of current A/C systems and the potential influences of alternative systems. Compressor (and therefore A/C system) load varies with a number of operating and design factors. Among these are cooling demand (which is a function of solar radiation, ambient temperature, and humidity), compressor displacement (which is generally a function of vehicle size), compressor shaft speed (which varies with engine speed), airflow (which varies with vehicle speed), and system operating mode (fresh air mode versus recirculation mode). Figure D-1, developed by W.O. Forrest at Delphi, illustrates the typical magnitude of such variation for an A/C system utilizing a freeze point controlled FDC of 210 cubic centimeters (cc) displacement. [5]

For this assessment, a vehicle miles of travel (VMT) weighted average set of evaluation conditions has been developed to compare alternative A/C system operational emissions. Impacts in most areas will, of course, vary somewhat from those estimated, in accordance with local conditions. In an effort to characterize the practical extent of this variation, the assessment also includes emission estimates for areas with below and above average cooling demands. Data from the National Renewable Energy Laboratory (NREL) were used to quantify typical vehicle cooling demands in the U.S. [7] NREL subjected meteorological data for a geographically diverse set of U.S. cities to detailed "thermal comfort" analysis to estimate the frequency and conditions associated with typical vehicle A/C usage. Table D-2 presents the resulting estimates.

Figure D-1: Illustrative Variation in Power Demand for a Pneumatically Controlled 210 cc FDC A/C System [5]



Note: The power demand figures include the effect of compressor "on/off" cycling as required to maintain efficient evaporator function.

Table D-2: Frequency of Use and Typical Conditions during A/C System Operation

State	2002 Annual VMT (million miles)	Number of Cities Represented	Percent of VMT with A/C On	Average Conditions when A/C Operating			
				Temperature (degrees C)	Temperature (degrees F)	Relative Humidity (percent)	Specific Enthalpy (kJ/kg)
United States	2,855,756	116	34	25	77.0	69	60.9
Louisiana	43,295	2	50	27	80.6	81	73.8
Florida	178,367	4	57	27	80.6	80	73.2
Alabama	57,515	4	43	27	80.6	76	71.5
Mississippi	36,429	1	52	27	80.6	75	70.6
Tennessee	68,229	3	40	27	80.6	74	70.5
Hawaii	8,886	1	69	27	80.6	73	69.0
Arkansas	30,080	1	43	27	80.6	72	68.8
Kansas	28,443	2	33	27	80.6	69	68.5
Oklahoma	45,731	2	40	27	80.6	69	68.2
South Carolina	47,290	1	50	27	80.6	70	67.7
Texas	221,026	11	49	27	80.6	69	67.6
Georgia	108,321	5	41	26	78.8	74	67.3
Missouri	68,163	3	33	26	78.8	74	67.2
North Carolina	92,894	3	38	26	78.8	74	67.1
Nebraska	18,719	1	26	25	77.0	76	65.5
Maryland	57,249	1	28	26	78.8	71	64.6
Virginia	77,450	2	31	25	77.0	77	64.3
Kentucky	46,841	2	30	25	77.0	75	64.1
Indiana	72,523	3	32	25	77.0	74	63.7
Iowa	30,847	1	26	25	77.0	71	62.4
Illinois	105,401	4	25	25	77.0	71	62.0
Delaware	8,875	1	28	25	77.0	72	61.7
West Virginia	20,005	1	27	24	75.2	77	61.7
Pennsylvania	104,476	3	26	25	77.0	71	61.6
New Jersey	69,942	2	23	25	77.0	69	60.2
Minnesota	54,562	1	20	24	75.2	73	60.0
Ohio	107,861	5	25	24	75.2	72	59.5
New York	133,057	4	21	25	77.0	67	59.3
Connecticut	31,205	2	21	24	75.2	73	59.1
Michigan	100,144	4	24	24	75.2	71	58.8
South Dakota	8,499	1	23	25	77.0	63	58.7
Wisconsin	58,746	2	17	23	73.4	77	58.6
Rhode Island	8,142	1	17	24	75.2	71	58.0
North Dakota	7,336	2	19	24	75.2	67	57.4
Massachusetts	53,266	2	16	23	73.4	71	54.9
Vermont	9,677	1	18	23	73.4	70	54.8
New Mexico	22,789	1	32	26	78.8	42	53.5
Arizona	51,334	2	58	30	86.0	32	52.9
Montana	10,395	1	18	25	77.0	47	51.7
Colorado	43,545	3	21	24	75.2	47	51.3
Wyoming	9,007	1	15	23	73.4	50	51.1
California	320,942	7	29	22	71.6	68	50.8
Utah	24,564	1	26	26	78.8	37	49.2
Maine	14,727	1	37	23	73.4	57	48.6
Nevada	17,966	2	41	23	73.4	52	48.5
Oregon	34,578	3	42	23	73.4	56	48.2
Idaho	14,167	1	23	25	77.0	37	45.7
Washington	54,776	2	25	21	69.8	58	44.4
New Hampshire	12,578	1	19	26	78.8	31	42.8
Alaska	4,896	1	6	17	62.6	67	37.6

Notes: (1) VMT data are from the Federal Highway Administration, *Highway Statistics 2002*. [15]

(2) Data for the number of cities from which state data are developed, percent of VMT with A/C operating, average temperature and average humidity with A/C operating are from the National Renewable Energy Laboratory. [5]

(3) Data on the specific (ambient) enthalpy with A/C operating are calculated from average temperature and humidity data, in conjunction with calculated standard atmospheric pressure for the population-weighted elevation of represented cities.

As indicated in Table D-2, the NREL data estimate state-specific VMT-weighted average temperature and relative humidity during A/C operation to range from 63-86ºF (17-30ºC) and 31-81 percent respectively. Weighting the individual state data by VMT, produces estimates of U.S. average conditions during A/C usage of 77ºF (25ºC) and 69 percent relative humidity. Because both temperature and humidity affect the amount of energy that must be removed (as heat) from ambient air to produce a desired level of cooling, the conversion of these data to specific enthalpy provides a more robust measure of average cooling demand for a given area. Specific enthalpy indicates the energy per unit mass, which for ambient air can be calculated from temperature and humidity data at a given atmospheric pressure. The NREL data available for this assessment did not include pressure data, so pressures were estimated for each of the 116 cities in the NREL dataset on the basis of elevation and standard U.S. atmospheric pressures. The resulting estimates of specific enthalpy during A/C system use are presented in Table D-2, and range from about 38-74 kilojoules (kJ) per kilogram (kg). The U.S. average estimate is 61 kJ/kg. It should also be noted that solar load also affects A/C usage. Local solar load is considered by NREL for each of the 116 U.S. cities in their dataset and is reflected in Table A-2 through its impact on the parameter "percent of VMT with A/C on."

As shown in Figure D-1 above, A/C compressor power consumption varies with ambient conditions. Using the NREL data to reflect average ambient operating conditions, average compressor power consumption can be estimated. Essentially, this involves interpolating between the various consumption curves presented in Figure D-1 to arrive at a typical average consumption rate. The temperature and humidity test conditions defined in Figure D-1 can be converted to approximate specific enthalpies as shown in Table D-3. From these data, it is clear that tests conducted at 27ºC (80.6ºF) and 60 percent relative humidity differ from U.S. average A/C operating conditions by only about 2 percent. Moreover, high average A/C use conditions typical of the southeastern U.S. (Louisiana in particular) are approximately midway between A/C system tests conducted at 32ºC (89.6ºF) and 50 percent relative humidity and 38ºC (100.4ºF) and 40 percent relative humidity. Finally, A/C system tests conducted at 16ºC (60.8ºF) and 80 percent relative humidity are within 4 percent of the low average A/C usage conditions encountered in Alaska.

Because weather extremes in the U.S. can vary from average by a significant extent, it is important to evaluate the potential impact of such extremes. Temperatures in southwestern states such as Arizona can climb above 110ºF fairly often in the summer months. However, during these excursions, humidity levels are generally limited to about 20 percent or lower. As indicated in Table D-3, the approximate enthalpy for 45ºC (113ºF) and 20 percent relative humidity is about 77 kJ/kg, or about 4 percent higher than the high average A/C use conditions representative of the southeastern U.S. Thus, it appears that the range associated with average A/C usage conditions across the U.S. is quite robust in its ability to reflect the broad range of A/C operating conditions.

Using these data, representative A/C system operational GHG impacts can be estimated. However, since A/C system design varies across vehicles, it is first necessary to develop a representative A/C system. Although there is limited penetration of VDC-based systems, pneumatic freeze point controlled FDC-based systems continue to dominate the U.S. market. Thus, the baseline A/C system for this assessment is a

Table D-3: Approximate Enthalpies of Typical A/C System Test Conditions

Test Conditions	Temperature (degrees C)	Temperature (degrees F)	Relative Humidity (percent)	Specific Enthalpy (kJ/kg)
Figure D-1 -- Condition 1	38	100.4	40	82.3
Figure D-1 -- Condition 2	32	89.6	50	71.4
Figure D-1 -- Condition 3	27	80.6	60	62.2
Figure D-1 -- Condition 4	22	71.6	70	52.3
Figure D-1 -- Condition 5	16	60.8	80	39.6
Figure D-1 -- Condition 6	10	50.0	90	27.8
Comparable Ambient Conditions				
U.S. Average A/C Conditions	25	77.0	69	60.9
U.S. High Average (Louisiana)	27	80.6	81	73.8
U.S. Low Average (Alaska)	17	62.6	67	37.6
U.S. High Temperature	45	113.0	20	77.0
SC03 Cycle Conditions	35	95.0	40	72.3

pneumatic freeze point controlled FDC-based system. Compressor displacement varies considerably across the U.S. market. The smallest cars can utilize compressors with displacements below 150cc, while larger light trucks can rely on compressor displacements over 200 cc. For this evaluation, it is assumed that typical compressor sizes range from about 150 cc for a compact car to 210 cc for a large SUV, so that average compressor displacement is about 180 cc given current vehicle sales shares. Since A/C system load is approximately proportional to compressor displacement, the use of a single average compressor displacement should produce reasonably accurate fleet average GHG impact estimates given the overall uncertainty associated with the various A/C system operational and emission parameters. As a result, a single 180 cc displacement pneumatically controlled FDC system was evaluated.

Evaluations were also performed for several alternative systems. The initial alternative to the baseline HFC-134a system is an enhanced HFC-134a system that takes advantage of available efficiency improving technologies. For this evaluation, an externally controlled VDC-based system with automatic air recirculation was evaluated as the enhanced system. Other approaches such as improved heat exchangers or externally controlled FDC-based systems with rapid cycling algorithms may be able to provide similar levels of improvement, but the intent of the evaluation was not to proscribe specific technological approaches, but to evaluate viable CO_2 reduction levels. Therefore, while the levels of CO_2 emissions developed for this evaluation are based on the comparison of an internally controlled FDC system to an externally controlled VDC system, it is the CO_2 emissions levels that are of interest, not the specific technology path undertaken to achieve them.

The efficiency improvement that could result from the use of externally controlled VDC systems with automatic air recirculation was evaluated using existing research data as presented in Figures D-2 and D-3. Figure D-2, as developed by W.O. Forrest and M.S.

Bhatti at Delphi, presents the relative power consumption of comparable A/C systems utilizing a variety of technologies, including a pneumatically controlled FDC system, both pneumatically and externally controlled VDC systems, and an externally controlled VDC system in combination with air management strategies. [6] The test conditions for these data are virtually identical to U.S. average A/C operating conditions. Figure D-3, also developed by Forrest, illustrates how the compressor power requirements of an externally controlled VDC system in combination with enhanced air management strategies vary with ambient conditions. [5] The variation in compressor power with changing ambient conditions for a comparable pneumatically controlled FDC system was previously presented in Figure D-1 above. It is important to recognize that these figures are illustrative only in that they are based on systems that are larger than that assumed for an average A/C system in this evaluation. This evaluation assumes a 180 cc average pneumatically controlled FDC system displacement, and all system load estimates have been adjusted to reflect this reduced displacement.

To accurately consider the impacts of an enhanced externally controlled VDC-based system employing an air intake management strategy to force cooled air recirculation, the relations presented in Figures D-1, D-2, and D-3 were adjusted to reflect a 180 cc base FDC system as well as to factor out the benefits of a reduced reheating strategy (since the impacts of series reheat were not assumed in the baseline A/C system consumption).[41] As indicated in Figure D-2, the efficiency benefits of air intake management are expressed incremental to those of reduced reheating. To factor out the reduced reheating efficiency benefits, the ratio of power demand with both reduced reheat and air intake management to power demand with only reduced reheat was applied to VDC power demand without either the reduced reheat or air intake management strategies. Similarly, the base (180 cc) system displacement adjustment was accomplished by normalizing the power demands for the VDC system to those of the corresponding base FDC system and treating the normalized power demand as representative of the efficiency benefits associated with a non-specific FDC system replacement.

Since the power consumption of both internally and externally controlled A/C systems varies with both engine speed and ambient conditions as indicated in Figures D-1 and D-3, the relationships presented in those figures must be processed to derive estimated consumption impacts for a given set of conditions. For this study, the curves presented in Figures D-1, D-2, and D-3 were reconfigured to estimate power demand over a range of ambient conditions at a single engine speed of 1500 rpm. Demand at

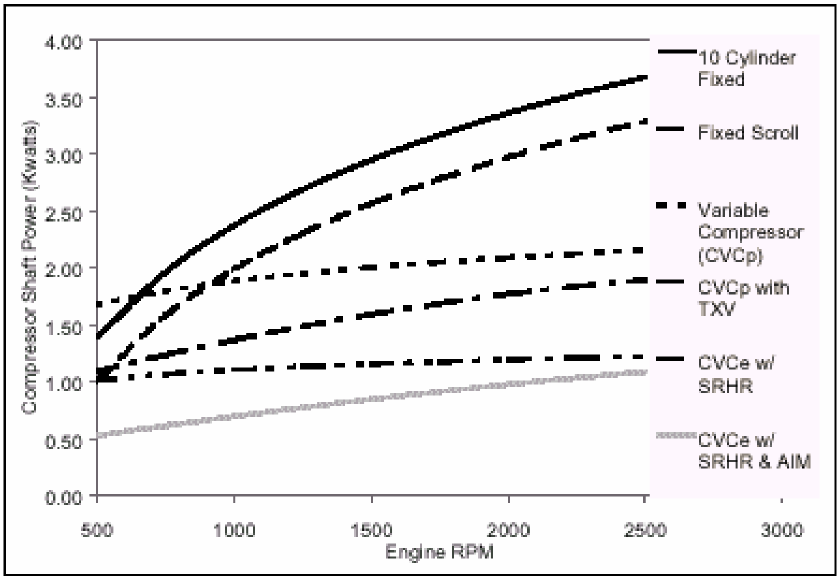
[41] It should be noted that in the enhanced externally controlled A/C system, the combination of external control, variable compressor displacement, and automatic air management do derive significant efficiency improvements through a reduction in the level of series reheat required to maintain a given passenger cabin temperature. However, since this study assumes a manually controlled baseline A/C system for which the impacts of series reheat were assumed to be minimal, it was appropriate to exclude the efficiency benefits from reduced series reheat from the impact calculations *of this study*. This does not imply that these benefits will not accrue, simply that no credit for them is taken in this study. In effect, the efficiency benefits for the enhanced A/C system assumed in this study relative to a baseline system *in which series reheat is significant* (i.e., an automatic climate control system) will be greater than estimated in this study. For example, while this study estimates a power consumption reduction of about 55 percent for the enhanced A/C system, Forrest and Bhatti estimate a reduction of 75 percent for the exact same system [6].

1500 rpm was selected as most appropriate for a determination of *average* U.S. impacts based on an analysis of engine speeds over typical driving cycles. Figure D-4 presents the resulting power demand curves.

As might be expected, the power demand curves show the greatest benefit of externally controlled VDC systems to be in the mid range of typical ambient conditions encountered during A/C system operation. At ambient conditions inducing higher cooling demand, the operating displacement of the externally controlled VDC system approaches that of an internally controlled FDC system and benefits decline. Benefits also decline at low ambient, low cooling demand conditions because the on time for an internally controlled FDC clutch cycling system is small, thereby reducing the level of excess power demand available for reduction. Using the presented relationships, the specific efficiency improvements for an externally controlled VDC-based A/C system employing an air intake management strategy can be estimated for average, high average, and low average U.S. A/C operating conditions.

Alternative Refrigerant Impacts on Energy Demand: HFC-152a has been shown to have physical, thermodynamic, and transport properties similar or superior to those of HFC-134a, while the corresponding properties for hydrocarbon refrigerants are generally also similar or superior to the hydrofluorocarbon refrigerants. Thus, A/C systems utilizing HFC-152a or propane refrigerants should be

Figure D-2: Variation in Power Demand for Various A/C System Technology Relative to a 215 cc Pneumatically Controlled FDC System [6]



Note: The power demand figures include the effect of compressor "on/off" cycling as required to maintain efficient evaporator function at ambient conditions of 26.7ºC (80.1ºF) and 60 percent relative humidity (approximately 61 kJ/kg specific enthalpy). "CVC" stands for Compact Variable Compressor, "p" stands for pneumatically controlled, "e" stands for externally controlled, "SHSR" stands for Series Reheat Reduction Strategy, "AIM" stands for Air Inlet Mixture (i.e., forced recirculation), and "TXV" stands for Thermal Expansion Valve.

Figure D-3: Ambient Impacts on Power Demand for an Externally Controlled VDC System with Enhanced Air Management [5]

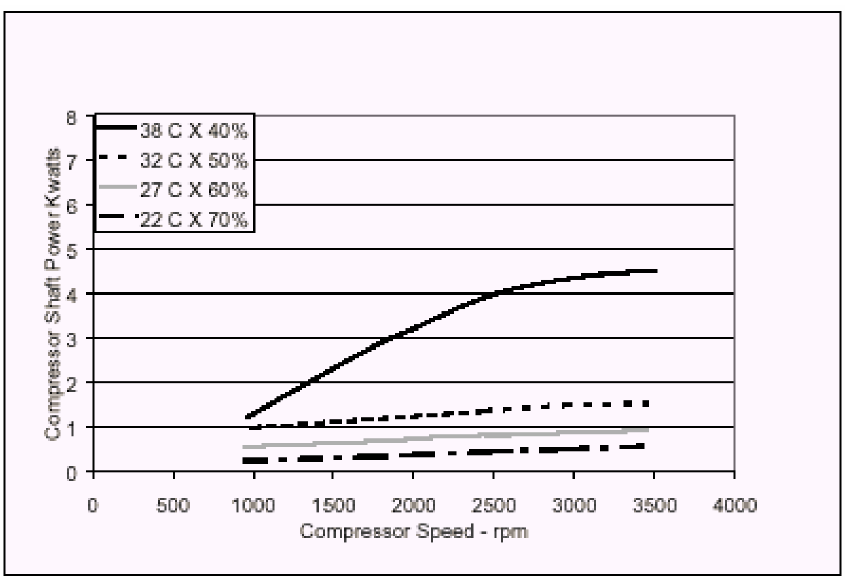
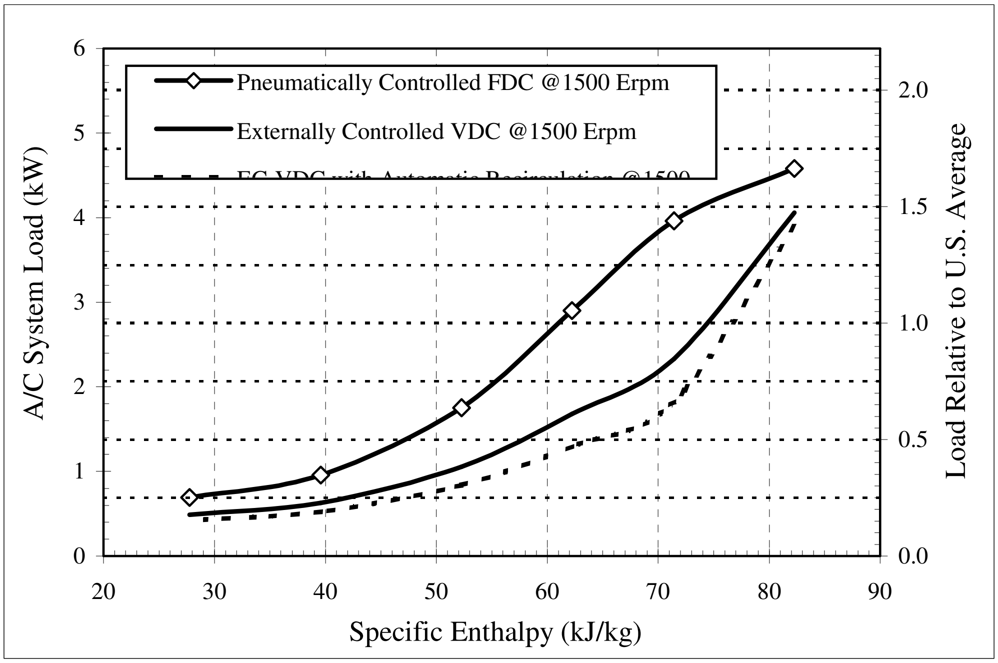


Figure D-4: Power Demand for the Pneumatically Controlled FDC and Externally Controlled VDC Systems at 1500 rpm Engine Speed



capable of transferring heat more efficiently than similar HFC-134a systems. Existing research for HFC-152a appears to confirm this, where data consistently show improved efficiency. [14,16-18] Moreover, it appears that this improvement increases with ambient enthalpy. A regression analysis of available data shows an 11 percent efficiency improvement for enthalpies in the 80 kJ/kg range, declining to about 5 percent in the 60 kJ/kg range. Because available evaluation data were limited to the lower end of this range, the regression was not extrapolated, but instead held constant at a 5 percent improvement for low enthalpy conditions.

As with HFC-152a, there is limited available data for propane systems. [14,18] A regression analysis of available data indicated no significant slope, so a simple arithmetic average was selected as the most appropriate approach to estimating power demand reduction for propane systems. The average reduction relative to HFC-134a systems is 3 percent.

The power demand impacts of CO_2-based A/C systems have been subject to considerable debate. Early theoretical calculations predicted poor performance for CO_2 systems relative to HFC-134a. [8] Those calculations were predicated on a series of thermodynamic properties of CO_2 (primarily its low critical temperature) that implied poor performance relative to HFC-134a. However, considerable research has demonstrated that in practice CO_2 systems can perform better than HFC-134a systems for a wide range of operating conditions. [19-21] This apparent discrepancy results from the fact that CO_2 possesses better heat transfer properties than HFC-134a, and CO_2 systems operate at reduced pressure ratios resulting in higher compressor efficiency. For this evaluation, recent research conducted at the University of Illinois was used to estimate CO_2 system power demand. [21] This research was selected specifically because it compares the performance of a CO_2 system to an enhanced HFC-134a system of equivalent compressor and evaporator design and size. Using these data, the estimated power demand reductions for average, high average, and low average U.S. A/C operating conditions are 8 percent, 1 percent, and 20 percent respectively.[42]

As mentioned above, HFC-152a, propane (as well as other hydrocarbon-based systems), and CO_2 A/C systems all present certain safety risks beyond those of HFC-134a systems. HFC-152a and propane are considered to be flammable (albeit HFC-152a to a lesser extent than propane), while CO_2 is considered to be toxic due to physiological effects at moderately high concentrations and its ability to asphyxiate at sufficiently high concentrations. A risk assessment for all three systems is currently being conducted through a cooperative government/industry process to determine the extent of imposed risk. Based on the results of that assessment, it is possible that one or more of these refrigerants may be restricted from use in traditional A/C systems where the system evaporator is located inside the passenger cabin (behind the instrument panel). Alternatively, the basic system design could remain unchanged, but added safety equipment could be required to detect and respond to refrigerant leaks (e.g., by automatically lowering vehicle windows). At this time, it is unclear how the risk assessment process will conclude.

Based on the current uncertainty regarding the level of risk imposed by HFC-152a, propane, and CO_2 systems, it is appropriate to examine the impacts of potential system designer response to possible risk constraints. One particular response, the use of secondary loop A/C systems, could significantly impact the power-demand estimates for each of the systems. In a secondary loop system, the primary system refrigeration loop is analogous to current A/C system designs, except that: (1) it is located entirely outside the passenger cabin, and (2) the evaporator is coupled to a secondary fluid refrigeration loop rather than cabin-bound air ducts. The secondary loop fluid, generally a water/glycol mixture, transfers heat from passenger cabin-bound air to the primary refrigerant. Thus, the secondary loop system isolates the passenger cabin from the primary refrigerant, but also adds complexity and incremental power demand. The incremental power demand is due to both a pump required to move the secondary fluid through its circuit and the incremental efficiency losses associated with an additional heat exchange operation.

Research has been performed to evaluate the power demand impacts associated with secondary loop systems. [14, 16] Although empirical data are somewhat limited, there is sufficient consistency to indicate that incremental demand is on the order of 10-25 percent. Since regression analysis indicates no significant slope between power

[42] It should be noted that subsequent to the completion of the A/C portion of this study, summary data from the SAE Alternate Refrigerant Cooperative Research Program (ARCRP) were released. The ARCRP was initiated by the Society of Automotive Engineers (SAE) to evaluate the energy efficiency of various mobile A/C systems. The released summary data imply a CO_2 efficiency benefit of about 7 percent relative to an enhanced HFC-134a system, quite consistent with the 8 percent benefit assumed in this study.

demand impacts and system operating conditions, incremental system power demand was estimated through arithmetic averaging at about 18 percent.[43]

Costs: Estimating the cost of the A/C system alternatives is somewhat difficult given the research nature of most of the evaluated options. Nevertheless, previous researchers have produced some estimates. [22, 23] However, in many cases, biases have been demonstrated in favor of one option or another and, as a result, it is sometimes difficult to rationalize the various available cost estimates. For example, the cost of an incremental safety system may be applied to one refrigerant and not another, or the costs of safety considerations overlooked entirely. In this evaluation, an attempt is made to correct for these inconsistencies so that presented costs may differ somewhat from those presented in the public references. Basically, the following cost assumptions are employed:

- The cost associated with the upgrade of current system components to a system that includes an externally controlled variable displacement compressor with electronic controls and reduced leakage hoses and connections is estimated to be $40. This cost applies to all evaluated A/C alternatives.

- HFC-152a and propane systems accrue no additional component costs, except as related to safety as noted below.

- CO_2 systems accrue an additional $20 cost associated with the upgrade of system hoses and components for higher pressure operating conditions, so that the total system component cost for CO_2 systems is estimated to be $60.

- For non-secondary loop designs, HFC-152a, propane, and CO_2 systems are assumed to require additional safety equipment, including in-cabin leak sensors and engine compartment evacuation valves. An additional cost of $22.50 is assumed for all three alternatives.

- For secondary loop designs, the incremental cost of a secondary loop is assumed to be $50 and this estimate is independent of the primary loop refrigerant. Thus HFC-152a, propane, and CO_2 systems with secondary loops all reflect this incremental cost. However, the added cost of the safety equipment described above ($22.50) is subtracted out of secondary loop systems, so that the net incremental cost is $27.50.

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[43] Here also, it should be noted that subsequent to the completion of the A/C portion of this study, summary data from the SAE Alternate Refrigerant Cooperative Research Program (ARCRP) were released. The ARCRP was initiated by the Society of Automotive Engineers (SAE) to evaluate the energy efficiency of various mobile A/C systems. The released summary data imply a secondary loop efficiency disbenefit of about 18-20 percent relative to an enhanced HFC-134a system. This is entirely consistent with the 18 percent estimate assumed in this study.

Based on these estimates, both the total incremental system cost for each A/C option as well as the cost per ton of associated CO_2 (or CO_2 equivalent) reductions can be estimated. presents the derived GHG reduction, cost, and cost effectiveness estimates. For convenience in comparing these data to other CO_2 control strategies, cost effectiveness estimates are presented both in terms of CO_2 and carbon. As indicated, for average U.S. A/C usage conditions, the cost effectiveness of the various A/C alternatives ranges from -8 to -43 dollars per ton CO_2 (-31 to -158 dollars per ton carbon), with the 40 gram enhanced HFC-134a system being the most cost effective.[44] However, the enhanced HFC-134a system provides only about 70-75 percent of the benefits of HFC-152a, propane, or CO_2 systems. In high average usage areas, the cost per ton drops even further due to the proportionally higher emission reductions associated with greater A/C system usage. Conversely, in low average usage areas, the cost per ton rises dramatically due to low system usage rates.

[44] Negative cost effectiveness estimates indicate a situation in which consumers derive a net cost savings through reduced fuel usage

Table D-4: Estimated A/C System GHG Reductions, Cost, and Cost Effectiveness

A/C System Type	Total Equivalent CO_2 (kg/year)	Total Equivalent CO_2 (kg/life)	Total CO_2 Reduction (kg/life)	Incremental System Cost ($)	Cost Benefit ($/ton CO_2) [see Note 2]	Cost Benefit ($/ton C) [see Note 2]
U.S. Average Operating Conditions						
Baseline HFC-134a	464.1	5,569.2	Baseline	0.00	Baseline	Baseline
Enhanced HFC-134a (40 gram/yr leakage)	260.6	3,127.2	2,442.0	40.00	-43.09	-158.01
Enhanced HFC-134a (20 gram/yr leakage)	229.6	2,755.2	2,814.0	40.00	-37.40	-137.12
HFC-152a (20 gram/yr leakage)	170.1	2,041.2	3,528.0	62.50	-25.22	-92.47
HFC-152a with SL (20 gram/yr leakage)	195.3	2,343.6	3,225.6	90.00	-13.95	-51.16
Propane (20 gram/yr leakage)	167.8	2,013.6	3,555.6	62.50	-24.62	-90.27
Propane with SL (20 gram/yr leakage)	194.7	2,336.4	3,232.8	90.00	-13.08	-47.96
CO_2 (porous)	164.8	1,977.6	3,591.6	82.50	-19.95	-73.16
CO_2 with SL (porous)	190.0	2,280.0	3,289.2	110.00	-8.42	-30.87
CO_2 (50 gram/yr leakage)	164.2	1,970.4	3,598.8	82.50	-19.91	-73.01
CO_2 with SL (50 gram/yr leakage)	189.4	2,272.8	3,296.4	110.00	-8.40	-30.80
High U.S. Average Operating Conditions						
Baseline HFC-134a	866.1	10,393.2	Baseline	0.00	Baseline	Baseline
Enhanced HFC-134a (40 gram/yr leakage)	520.2	6,242.4	4,150.8	40.00	-51.25	-187.91
Enhanced HFC-134a (20 gram/yr leakage)	489.2	5,870.4	4,522.8	40.00	-47.03	-172.45
HFC-152a (20 gram/yr leakage)	405.6	4,867.2	5,526.0	62.50	-38.84	-142.42
HFC-152a with SL (20 gram/yr leakage)	472.5	5,670.0	4,723.2	90.00	-29.47	-108.06
Propane (20 gram/yr leakage)	420.3	5,043.6	5,349.6	62.50	-37.46	-137.34
Propane with SL (20 gram/yr leakage)	489.8	5,877.6	4,515.6	90.00	-27.23	-99.86
CO_2 (porous)	429.5	5,154.0	5,239.2	82.50	-33.46	-122.68
CO_2 with SL (porous)	501.8	6,021.6	4,371.6	110.00	-21.91	-80.33
CO_2 (50 gram/yr leakage)	428.9	5,146.8	5,246.4	82.50	-33.41	-122.51
CO_2 with SL (50 gram/yr leakage)	501.2	6,014.4	4,378.8	110.00	-21.87	-80.20
Low U.S. Average Operating Conditions						
Baseline HFC-134a	146.5	1,758.0	Baseline	0.00	Baseline	Baseline
Enhanced HFC-134a (40 gram/yr leakage)	119.9	1,438.8	319.2	40.00	88.62	324.93
Enhanced HFC-134a (20 gram/yr leakage)	88.9	1,066.8	691.2	40.00	40.92	150.06
HFC-152a (20 gram/yr leakage)	34.7	416.4	1,341.6	62.50	36.19	132.68
HFC-152a with SL (20 gram/yr leakage)	40.5	486.0	1,272.0	90.00	61.22	224.48
Propane (20 gram/yr leakage)	30.5	366.0	1,392.0	62.50	34.88	127.88
Propane with SL (20 gram/yr leakage)	36.6	439.2	1,318.8	90.00	59.22	217.14
CO_2 (porous)	32.2	386.4	1,371.6	82.50	49.56	181.72
CO_2 with SL (porous)	38.1	457.2	1,300.8	110.00	74.86	274.48
CO_2 (50 gram/yr leakage)	31.6	379.2	1,378.8	82.50	49.30	180.77
CO_2 with SL (50 gram/yr leakage)	37.5	450.0	1,308.0	110.00	74.45	272.97

Notes: (1) SL signifies "Secondary Loop" and the indicated gram per year leakage defines the system design standard. Porous indicates a CO_2 system that is recharged annually and is included only to illustrate the insensitivity of CO_2 emissions performance to leakage rate. Lifetime emissions are based on a 12 year estimated life.

(2) Cost benefit calculations include accrued fuel savings due to indirect emission reductions, estimated using the following assumptions: 19.5 pounds CO_2 per gallon of gasoline, 12 years/150,000 miles vehicle life, 4.5 percent annual decline in travel, 12 years of fuel savings, $1.50 per gallon fuel price, and a 12 percent annual discount rate for future savings.

In considering overall A/C system GHG reduction potential, there are several issues that should be recognized. Each issue, however, could demand the focus of significant investigation beyond the scope of this evaluation. The following list presents a basic overview of a variety of these issues, and where appropriate indicates where estimates produced in this evaluation might be subject to uncertainty based on future related developments.

- *Basic* research into A/C approaches that differ fundamentally from the approaches included in this evaluation has been conducted. For example, basic theoretical work related to systems such as metal hydride heat pumps, absorption cycles, heat pipes, and turbocharger-driven compression has been reported. However, none of these approaches has achieved a level of development that allows an accurate determination of practical feasibility, impact, or cost to be estimated in any way that would allow for reasonable comparison to more advanced alternatives. For this reason, such options are not considered in this evaluation.

- Similarly, there are a number of vehicle design parameters unrelated to the A/C system itself that affect A/C energy demand. For example, cabin design, window glazing, interior color, instrument panel design, cabin ventilation, and myriad other parameters can all affect occupant comfort and, therefore, A/C demand. Although worthy of investigation, the analysis of the cost effectiveness of such design strategies relative to the cost of more efficient A/C systems is beyond the scope of this evaluation.

- The feasibility of onboard diagnostic (OBD) systems to detect reduced refrigerant charge levels has been demonstrated and such systems could be used to enforce mandated refrigerant leakage rates if imposed. Such systems would add costs beyond those assumed in this evaluation, but could be considered as part of a regulatory program that, for example, might allow the continued use of HFC-134a with appropriate low level OBD detection safeguards.

- The ability to CO_2 systems to retain a specified charge over time has not yet been demonstrated in use. CO_2 systems operate at much higher pressures than current vapor compression systems and this poses a significant leakage challenge for CO_2 system designers. Typical operating pressures for CO_2 systems are about 500-700 psia on the low pressure side and 1400-1900 psia on the high pressure side, as compared to 40-65 psia on the low pressure side and 200-350 psia on the high pressure side for HFC-134a systems. Thus, CO_2 systems must be able to prevent refrigerant leakage while operating at pressures 7-10 times greater than those of current systems. While prototype systems have been developed and tested, some uncertainty remains about the ability of CO_2 systems to perform adequately in consumer use. It should be noted that this primarily a marketability issue, and is not important from an emissions perspective. To demonstrate this fact, this evaluation included a "porous" CO_2 system that required a complete refrigerant refill annually and, as presented above, the emissions performance of this system is virtually identical to a "tight" CO_2 system. However, the cooling performance is the critical factor from a consumer perspective and a porous system is not a viable A/C alternative. Based on progress to date, it seems likely that adequate system design can be achieved, but the issue should not be dismissed at this point in system development.

- The ability of HFC-152a, propane, and CO_2 systems to meet acceptable safety requirements is currently being evaluated. Both HFC-152a and propane represent potential flammability concerns, while CO_2 presents toxic concerns related to mental acuity and asphyxiation. Possible responses include the installation of safety systems, which have already been demonstrated, or the use of secondary loop A/C systems. This evaluation includes the effect of both approaches on estimated system performance and cost, but it in unclear whether an ongoing government/industry risk assessment will conclude that either approach is adequate to address all safety issues.

- Electric A/C compressors may offer further efficiency advantages over current belt driven systems. These advantages primarily result from the ability to control compressor speed independent of engine speed, which becomes especially important on hybrid electric vehicles (HEV) and conventional gasoline vehicles utilizing engine-off at idle technology. Adapting A/C system capacity to cooling demands through compressor speed variation, as opposed to the compressor displacement variation approach employed in VDC systems, offers volumetric efficiency advantages that result in additional reductions in system energy-demands. Some of the volumetric efficiency gain is lost to reduced power transmission efficiency (electric drive efficiencies are typically in the 65 percent range, whereas belt drive efficiency generally exceeds 95 percent), but it appears that the net gain could be positive. However, current 12 volt electric systems are not adequate to handle the additional power demands imposed by electric compressors. Migration of vehicles to 42 volt systems, as is being discussed for a variety of power consumption reasons other than A/C, would enable electric compressor use. However, given the uncertainty of a 42 volt future in the 2009-2015 timeframe of this study, electric compressors have not been considered as a large market A/C option. Nevertheless, electric A/C systems can be expected to achieve a modest level of market penetration in accordance with HEV, 42 volt, and engine-off at idle technology.

- As described above, the current A/C system technology for this evaluation was assumed to utilize pneumatically controlled fixed displacement compressor technology. However, it should be recognized that there are current variable displacement compressor systems in the U.S. market and that the externally controlled VDC market share can be expected to increase through the 2009-2015 timeframe. In the absence of regulatory consideration of A/C system impacts on fuel consumption, vehicle manufacturers have little incentive to switch to VDC systems for fuel consumption benefits. However, in some cases, manufacturers do have an incentive to switch to external control VDC systems to improve vehicle driveability and "feel." The incremental engine load associated with FDC clutch cycling is sufficiently large on small output engines to cause perceptible and perhaps unacceptable driveability concerns for some vehicles and customers. Thus, some manufacturers have been moving toward VDC systems in the small engine market to improve customer acceptance. In markets dominated by small displacement engines such as Europe and Japan, the market share of VDC systems is growing dramatically, but this same level of growth is not expected in the U.S. Average engine displacement in the EU is less than 2 liters, as opposed to nearly 3.5 liters in the U.S., with only about 6 percent of U.S. light duty vehicle sales reflecting engines under 2 liters displacement. Since larger engines respond less dramatically to compressor clutch cycling, the performance-based incentive for VDC systems is substantially less in the U.S. For example, even if VDC systems were installed on *all* light duty vehicles with displacements of 2 liters or less, the total U.S. new vehicle market share of VDC systems would be less than 15 percent through the 2009-2015 timeframe. If application was extended to *all* engines of 2.5 liters or less, the market incentive would double to about 30 percent, further increasing to about 40 percent at 3 liters or less. Given continuing dominance in the U.S. market, a pneumatically controlled FDC-based system was utilized as the baseline A/C system technology in this evaluation. Nevertheless, it should be recognized that some fraction of the U.S. market already incorporates VDC technology and that this presence will impose a modest error on total fleetwide emission impacts derived from the evaluation-assumed baseline conditions.

- Some research cites the ability of CO_2 systems to also perform in reverse (as heat pumps) and provide vehicle heating benefits as a major benefit of moving to CO_2 systems. Such ability would be most important in high efficiency vehicle applications with low waste heat availability. This evaluation has not considered such benefits for two primary reasons. First, it is not clear that operating the A/C compressor to support heat pump operation is the most efficient approach to supplying vehicle heat. Clearly, such operation would increase A/C system usage rates dramatically. Second, the ability of a CO_2 system to operate as a heat pump is not unique. Existing residential and commercial applications, as well as recent vehicle research, demonstrates that vapor compression cycle refrigerants possess the same ability.

- In accordance with the costing methods for other portions of this study, alternative A/C system costs include only the estimated high volume variable costs of components and do not consider the fixed costs associated with system introduction (e.g., engineering, and any incremental production, manufacturing, or assembly plant costs). For A/C systems, fixed costs to the vehicle manufacturer should be modest since the systems are generally purchased from suppliers and not manufactured by the vehicle manufacturer. Nevertheless, this approach can result in the omission of barriers to marketability and should be considered accordingly. Similarly, costs external to initial vehicle manufacture have also not been considered. This primarily involves service industry costs such as the cost of replacing recycling equipment, diagnostic tools, etc., but can also include additional consumer costs if service and maintenance differences exist across system alternatives. These omitted costs can vary considerably across the various systems. For example, with the exception of the potential replacement of the system desiccant to ensure compatibility, HFC-152a can effectively be used in current HFC-134a systems (i.e., it is virtually a "drop-in" replacement). With HFC-152a and propane, service equipment will need to be upgraded or replaced and both HFC-134a and alternative refrigerant equipment will need to be maintained during the switchover period. In the case of CO_2 systems, the service industry should incur no need for recycling equipment, but will require leak detectors and appropriate high pressure service equipment. However, if service intervals are shorted for CO_2 systems, consumers would incur additional costs.

- As stated previously, this evaluation assumes effective refrigerant recycling in both vehicle service and end-of-life disposal practices. If actual practices are ineffective, direct refrigerant emission impacts will be up to 3.5 times greater than estimated in this study, and total GHG impacts (direct plus indirect) will increase by about 50 percent for U.S. average operating conditions. The potential impacts of enforcing refrigerant recycling should be considered in the overall evaluation of alternative refrigerants. The negative effects of ineffective recycling practices decline in step with the GWP of A/C system refrigerant, so that the potential negative impacts of HFC-152a, propane, and CO_2 systems are significantly less than those for HFC-134a systems. CO_2 systems reflect a lower bound risk since direct emissions from CO_2 systems have a zero net GWP, allowing the complete elimination of refrigerant recycling requirements.

- Finally, the evaluation also does not consider emissions resulting from the energy used to produce refrigerants. Refrigerant leakage prior to vehicle charging is considered in the estimation of direct emissions, but energy used to power manufacturing and distribution equipment is not considered. Generally, all alternatives will require energy to produce and it may be that energy required to produce natural fluids such as CO_2 will be somewhat less than that required to produce HFCs, but such analysis is beyond the scope of this evaluation.

D.1.1. AVL CRUISE Simulation Modeling

To validate the analytical estimates of the stand-alone evaluation, several CRUISE simulations were conducted for baseline HFC-134a systems using pneumatically controlled FDC technology and alternative HFC-152a systems using externally controlled VDC technology with automatic air recirculation. To facilitate the simulation modeling, compressor power demand curves were developed for each of the A/C systems. Initial compressor demand estimates were developed from the curves presented previously in Figure D-2, which indicate the demands of several alternative system designs including those investigated in this exercise.

All CRUISE modeling related to A/C was performed for U.S. average ambient conditions during A/C operations, which as described above are estimated to be equivalent to a specific enthalpy of 60.9 kJ/kg. The data summarized in Figure D-2 are associated with ambient test conditions of 80.1 °F and 60 percent relative humidity, which is equal to a specific enthalpy of approximately 61 kJ/kg. Accordingly, the data presented in Figure D-2 are quite consistent with average U.S. operating conditions and no adjustments for ambient conditions were employed.

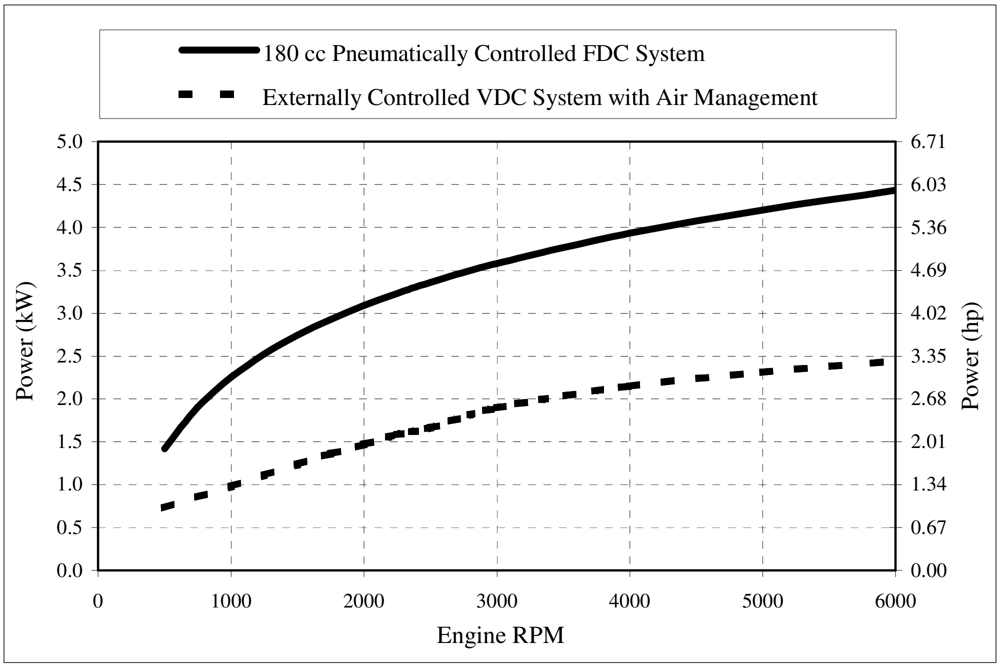
Nevertheless, several adjustments unrelated to ambient conditions were undertaken. First, the data presented in Figure D-2 correspond to a 215 cc base compressor displacement. First, power demands were scaled down to reflect a more "typical" 180 cc system using a simple proportionality approach. Second, since Figure D-2 presents data at the compressor shaft, engine crankshaft power was estimated by applying a power transmission efficiency factor. For this adjustment, a belt transmission efficiency of 97 percent was assumed. Third, the impacts of a "reheat reduction strategy" (designated as SRHR in Figure D-2) were removed from CRUISE analysis by normalizing the "SRHR&AIM" (reheat reduction plus automatic air recirculation) loads to the "SRHR" (reheat reduction alone) and applying the resulting ratios to the externally controlled variable displacement compressor curve without either reheat reduction or automatic air recirculation.[45] Finally, the system power associated with the cabin blower motor was assumed to be 0.25 kW and was added to the resulting consumption curves for both the baseline pneumatically controlled FDC-based system and the alternative externally controlled VDC-based system.

Figure D-5 presents the resulting A/C load curves provided to AVL for CRUISE modeling. It is perhaps worth noting that these curves are analogous to those previously presented in Figure D-4, except that engine speed is held constant in Figure D-4, while specific enthalpy is held constant in Figure D-5. The analytical evaluation described above assumed an average engine speed of 1500 rpm and estimated A/C GHG impacts

[45] As indicated in the discussion for the stand-alone analysis, series reheat reduction impacts are factored out of the impact calculations in this study, not due to a lack of expected benefits, but rather because the baseline system assumed in this study is a manually controlled A/C system for which series reheat is presumed to be minimal. Series reheat reduction should be an integral component of an enhanced system designed to maximize efficiency at an automatically controlled cabin temperature.

for various ambient conditions. The CRUISE simulations investigate only a single ambient condition (i.e., U.S. average), but treat engine speed on a robust basis according to the specific drive cycles evaluated.[46]

Figure D-5: A/C System Power Demand Versus Engine Speed



AVL performed several additional processing steps prior to actual CRUISE modeling. First, the generic 180 cc demand curves presented in Figure D-5 were converted into vehicle class specific curves in accordance with estimated class-specific compressor displacements of 150 cc for the small car class, 170 cc for the large car class, and 210 cc for all three truck classes.[47] As described above for the development of the 180 cc curves, this adjustment assumed proportionality between system power demand

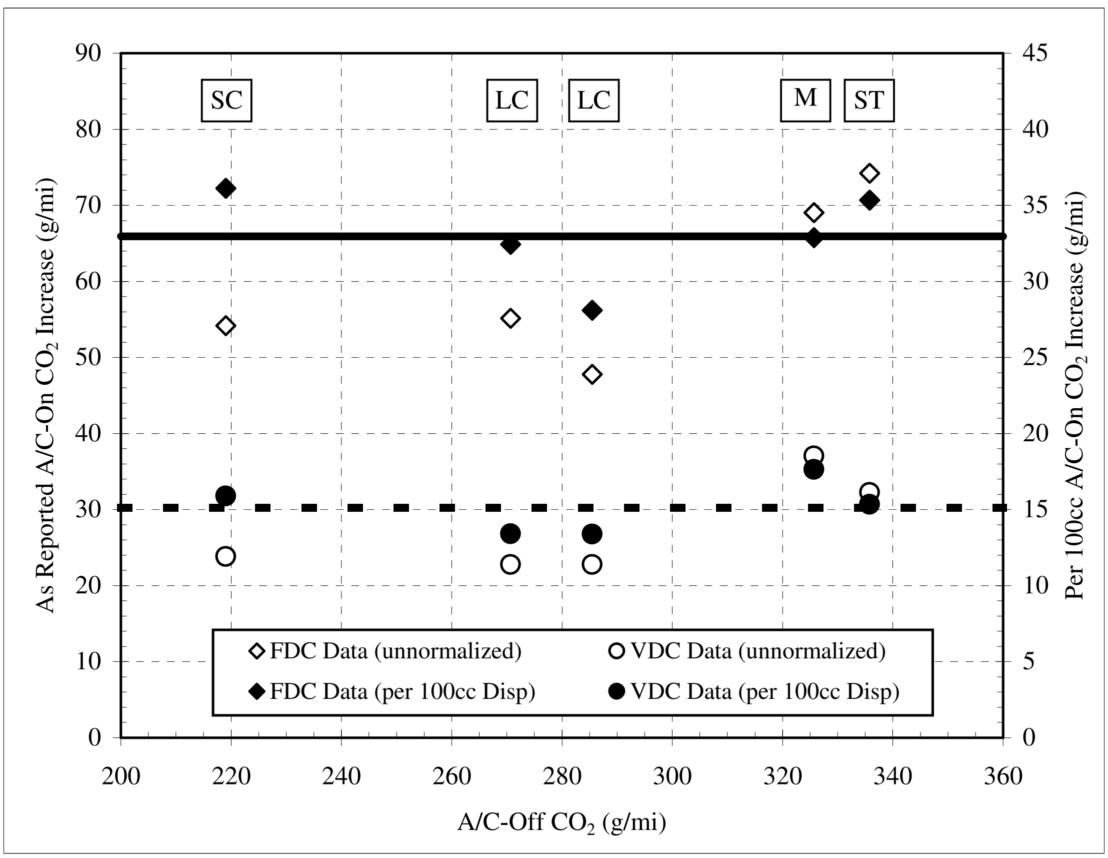
[46] It is perhaps worth noting that subsequent to the completion of the A/C portion of this study, summary data from the SAE Alternate Refrigerant Cooperative Research Program (ARCRP) were released. The ARCRP was initiated by the Society of Automotive Engineers (SAE) to evaluate the energy efficiency of various mobile A/C systems, and included the investigation of several advanced A/C systems relying on externally controlled VDCs and improved heat exchangers. Although the engine speeds covered by the summary data extend only from about 600-1700 rpm, the power consumption data for the ARCRP enhanced HFC-134a system over this speed range tracks quite closely with the power demand curve for the externally controlled VDC-based system used in this study (as presented in Figure D-5). Unfortunately, the ARCRP does not include comparable consumption data for a typical "unimproved" baseline A/C system.

[47] Actual compressor sizes in the truck classes cover a wide range of displacements, and 210 cc is probably near the upper end of the range. Therefore, the use of 210 cc as the compressor size for the three truck classes could overstate A/C-related energy consumption by 15-20 percent for a significant fraction of trucks. So, while the percentage improvement in A/C-related energy consumption is accurate for all vehicles in the truck classes, absolute CO_2 emissions due to A/C may be overstated by up to 5 grams per mile for the baseline A/C system and up to 2 grams per mile for the advanced system.

and compressor displacement. Second, AVL applied a 5 percent power demand reduction to the externally controlled VDC system curves for all five vehicle classes to simulate the benefit that is expected with HFC-152a refrigerant. Finally, AVL converted the class-specific demand curves into crankshaft torque curves and performed simulation modeling for both the baseline and alternative A/C systems by adding the A/C system loads to existing "non-A/C" simulations for two technology packages in the large car class and one technology package in each of the small car, small truck, and minivan classes.

Since A/C system simulation modeling was only performed for five of the technology packages, CRUISE results were investigated to determine if a generalized impact could be developed. Figure D-6 presents the impacts estimated by CRUISE for each of the five pneumatically controlled FDC system simulations and each of the five externally controlled VDC system simulations. The CRUISE outputs are indicated by the open markers (diamonds for the FDC system and circles for the VDC system). As indicated, there is considerable scatter for the FDC system, with estimated incremental CO_2 impacts varying by as much as 25 grams per mile (g/mi).

Figure D-6: CRUISE-Predicted A/C Impacts



Note: FDC in this figure refers specifically to a pneumatically controlled FDC-based A/C system. VDC refers specifically to an externally controlled VDC-based A/C system with enhanced air management.

Scatter for the VDC system is also significant, covering a range of about 15 g/mi. However, if the CRUISE outputs are adjusted to account for the differing compressor sizes across vehicle classes, much of the scatter goes away. This is reflected in the solid markers of Figure D-6 (diamonds for the FDC systems and circles for the VDC systems), where the full FDC scatter is now encompassed within a range of about 7 g/mi and the full VDC system scatter is encompassed within a range of about 5 g/mi.

Based on the resulting similarity in A/C system impacts per 100 cc compressor displacement, generalized A/C system impacts were estimated to be 33.0 g/mi per 100 cc for the base FDC system and 15.1 g/mi per 100 cc for the alternative VDC system. These impact estimates are also plotted in Figure D-6 as the solid and dashed lines respectively. As indicated, they represent the data for the five CRUISE simulations quite well. Accordingly, the generalized impact estimates are believed to be reasonable estimates of the impact of A/C systems on vehicle GHG for a wide range of technologies (as indicated in Figure D-6, the CRUISE modeling covered CO_2 emission rates ranging from 220 to 340 g/mi). On this basis, the generalized impact estimates have been applied to the full range of CRUISE simulation results presented in Chapter 3 above.

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Appendix E: Methane and Nitrous Oxide Emissions

Appendix E: Methane and Nitrous Oxide Emissions

E.1. Introduction

In addition to CO_2 emissions, which are discussed throughout the other sections of this report, light duty vehicle GHG emissions also include methane (CH_4) and nitrous oxide (N_2O). Although emissions of these compounds are generally orders of magnitude lower than emissions of CO_2, the global warming potential (GWP[48]) of both CH_4 and N_2O is greater than that of CO_2. Methane is estimated to have a GWP 23 times that of CO_2, while the GWP of N_2O is estimated to be 296 times that of CO_2. [1] As a result, it may be important to consider these emissions in determining the overall GHG impact potential of light duty vehicles.

Naturally emitted methane, principally a product of vegetative decay and digestive processes, is estimated to comprise about 40 percent of total atmospheric methane. The principal anthropogenic (manmade) methane sources in the U.S. are landfills, agriculture, coal mining, and natural gas extraction and distribution, which together account for over 90 percent of manmade emissions. In contrast, highway vehicles and nonroad equipment are estimated to produce less than one percent of manmade methane. Since 1990, manmade methane emissions in the U.S. are estimated to have declined by about 15 percent, primarily due to recovery practices in the coal and landfill industries. [2]

Almost 60 percent of N_2O emissions result from natural processes, primarily bacterial breakdown of soil nitrogen, ocean upwelling, and stratospheric photo-dissociation and oxidation.

Agricultural fertilization and solid waste denitrification are estimated to be responsible for the bulk of U.S. manmade N_2O emissions (about 70 percent), but nearly 20 percent are estimated to be produced by highway vehicles and nonroad equipment. Moreover, over 90 percent of the highway vehicle and nonroad equipment emissions share is estimated to be produced by light duty highway vehicles as a direct result of catalytic emissions conversion. Since 1990, manmade N_2O emissions in the U.S. are estimated to have remained mostly unchanged, although emissions from light duty vehicles have increased by about 30 percent (an increase offset by reductions in industrial and agricultural emissions). [2]

Methane emissions from vehicles represent a product of incomplete combustion.[49] Ideally, such emissions would be converted to CO_2 and water as they pass through the catalytic aftertreatment systems that are universally used on today's vehicles to meet

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48 GWP indicates the global warming effectiveness of a compound relative to that of CO_2, so that the GWP of a compound indicates the estimated ratio of its impact on global warming to the impact of the same mass of CO_2.

49 In the case of some automotive fuels, especially natural gas, methane comprises a substantial portion of the fuel itself. As a result, both incomplete combustion and fuel evaporation or venting can result in substantial methane emissions. Since this study focuses on gasoline and diesel vehicle emissions, methane-based fuels are not explicitly considered, but readers should recognize the increased methane emissions potential of such fuels.

existing criteria pollutant emission standards. However, as the simplest hydrocarbon, methane is less reactive than all other hydrocarbons and can pass through aftertreatment systems more easily than other hydrocarbon species. While catalyst system design can be tailored to more effectively convert CH_4, it is important to recognize that this conversion will *not* result in the reduction of methane-based GHG emissions to zero. Since catalytic action will produce 2.75 grams of CO_2 for every gram of methane converted, the elimination of unburned methane through catalysis can achieve a considerable net reduction in GHG, but that reduction is capped at 88 percent.[50,51] Of course, this same cap exists for improving in-cylinder fuel combustion characteristics, as any "displaced" methane will lead to an increase in CO_2 emissions. Only reduced fuel use can provide a complete reduction in methane-based GHG emissions.

N_2O emissions result almost entirely from activity within the catalytic aftertreatment systems of vehicles. Several test programs have demonstrated that engine-out N_2O emissions are consistent with background N_2O concentrations within the limits of detectability (approximately 0.01 grams per mile). [3-6] N_2O appears to be associated with low temperature NO_x (oxides of nitrogen) reduction, being formed as an intermediary reaction product.[52] [3,4] Although the body of research on the specific formation chemistry of N_2O is considerably less than that of other automotive emission species, the low temperature reaction mechanism is quite consistent with observed experimental emissions data. As a result, it is widely believed that the control of vehicle N_2O emissions is a function of improved aftertreatment systems.

A detailed discussion of vehicle methane emissions and the potential for future reductions follows in Section E.2. Section E.3 presents a similar discussion for N_2O emissions. Finally, Section E.4 presents a summary of associated conclusions.

E.2. Methane Emissions

As indicated in Section E.1, methane is emitted from light duty vehicles due to the incomplete combustion of fuel in the vehicle engine and the incomplete oxidation of engine-out methane in current catalytic aftertreatment systems. It is important to recognize, however, that current vehicles produce and emit substantially less methane than their older counterparts and, even in the absence of additional regulation, it is almost certain that future vehicles will exhibit even lower emission rates. Although there are currently no specific emission standards for methane, existing standards for non-methane organic compounds do effectively result in reduced methane emissions through the design and implementation of advanced combustion and catalyst technologies.

Emissions control of organic compounds has evolved over the years. While the latest (i.e., Tier 2 federal and LEV II California) standards are characterized in terms of non-methane organic gases (NMOG), other current (e.g., Tier 1 federal) and previous (e.g., Tier 0 federal) standards are, or have been, characterized in terms of non-methane

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[50] $(x\ CH_4)\times(23\ GWP) \rightarrow (2.75x\ CO_2)\times(1\ GWP)$, so maximum reduction potential = $[(2.75x)/(23x)]-1$ = 88 percent.

[51] Conversion of one gram of CH_4 also produces 2.25 grams of water, which is the most prevalent GHG. However, the GWP of methane accounts for its indirect production of water. [1]

[52] $2NO + CO \rightarrow N_2O + CO_2$, which ideally is followed by $N_2O + CO \rightarrow N_2 + CO_2$.

hydrocarbons (NMHC) or total hydrocarbons (THC). While only THC standards explicitly require the control of CH_4 emissions, since by definition both NMHC and NMOG exclude CH_4, all have effectively reduced methane emissions since the technologies and control strategies implemented to reduce NMHC also reduce the production and emission of methane. For example, engine technologies designed to reduce hydrocarbon emissions through improved combustion characteristics, reduce the full range of hydrocarbon emissions. Similarly, improved catalytic aftertreatment techniques that increase hydrocarbon conversion efficiency reduce both NMHC and methane emissions. While aftertreatment systems may preferentially oxidize NMHC due to its inherently higher reactivity, any improvement in oxidation efficiency will also increase the oxidation of methane. Therefore, even in the absence of explicit GHG-based limits, methane emissions should continue to decline as combustion and aftertreatment efficiencies are further improved.

Since methane emissions are measured as part of the standard vehicle certification process in the U.S., there is an extensive library of certification data that can be used to assess both the historic and current methane emission rates of light duty vehicles. Even so, a considerable degree of processing is required to assemble and analyze these data. For this study, a smaller 39 vehicle dataset developed by the California Air Resources Board (ARB) was utilized to estimate methane emission rates. [7] This ARB dataset was used for several reasons, including the following:

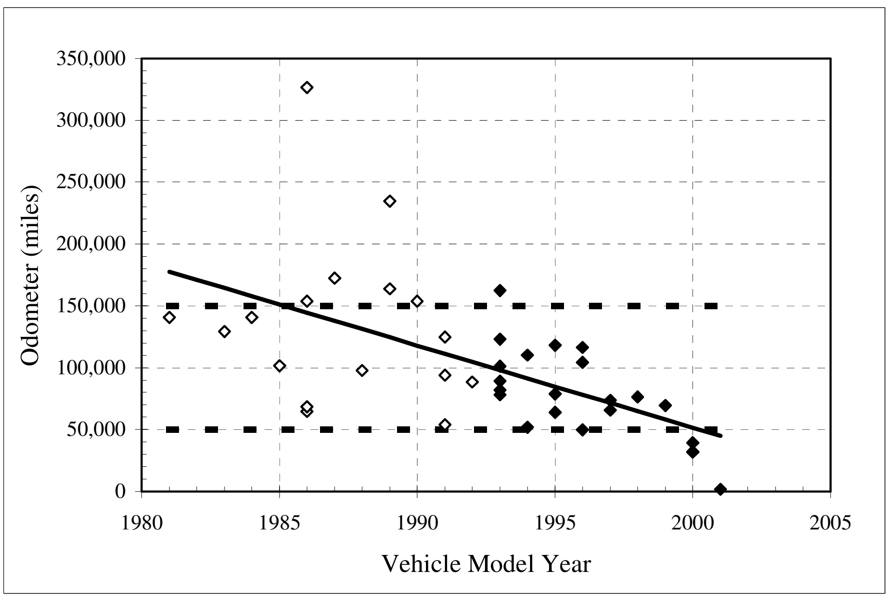
- The dataset represents emissions data for actual in-use vehicles and, therefore, provides an indication of actual in-use methane and N_2O emission rates.
- The dataset includes a wide range of vehicle model years, allowing a wide range of emissions levels to be analyzed.
- The dataset includes THC, NMHC, CH_4, NO_x, and N_2O emissions measurements for all 39 vehicles.

Generally, the ARB data was collected between 2000 and 2002 as part of the agency's 16th Vehicle Surveillance Program (VSP). Overall, the VSP, which is conducted periodically, is a much larger (than 39 vehicles) investigation of the in-use vehicle fleet, intended to evaluate such issues as the cost effectiveness of the state's vehicle emissions inspection program, in-use emissions deterioration rates, in-use evaporative emission rates, in-use speciation profiles, and alternative test cycles. This study looked at only a subset of the full VSP dataset, since N_2O emissions were not collected for all study vehicles. Moreover, only VSP data collected over the standard FTP-75 driving cycle were analyzed to avoid any potential confounding issues related to driving cycles. As indicated, these criteria constrain the overall dataset size to 39 vehicles.

The vehicles included in the VSP are California-based light duty vehicles. Since federal and California vehicle emission standards have varied over the years (and continue to do so), this might be cause for variation in estimated emission rates from those expected in the rest of the U.S. However, it is expected that any such variation will be minor for several reasons. First, for pre-1993 vehicles, the differences between the federal and California hydrocarbon standards are minor. Second, much of the federal fleet now consists of vehicles certified to the National Low Emissions Vehicle (NLEV) standards, which are similar to the California Low Emission Vehicle (LEV) standards. Third, the estimated emission rate is determined as an average across vehicles and the variation between individual vehicles is at least as large as the variation between federal and California standards. Finally, the data are primarily used to derive emission rate ratios as opposed to absolute emission rates. These ratios are then applied to applicable federal certification standards to develop expected federal emission rates, so that the absolute emission levels of the California data are primarily a reference point rather than a final emissions estimate.

Figure E−1 and Table E−1 provide an overview of the vehicle fleet represented in the VSP dataset used for this study. As indicated, vehicles span a 21 model year range of 1981 through 2001, with odometer readings ranging from 1,700 to 326,000 miles. Most of the 39 test vehicles (31) are passenger cars, but there are also 8 light duty trucks. Thus, trucks are underrepresented in the test sample. The test vehicles do, however, represent a wide range of engine sizes, with displacements ranging from one to five liters.

Figure E-1: Mileage and Model Year of Vehicles in the ARB VSP Dataset

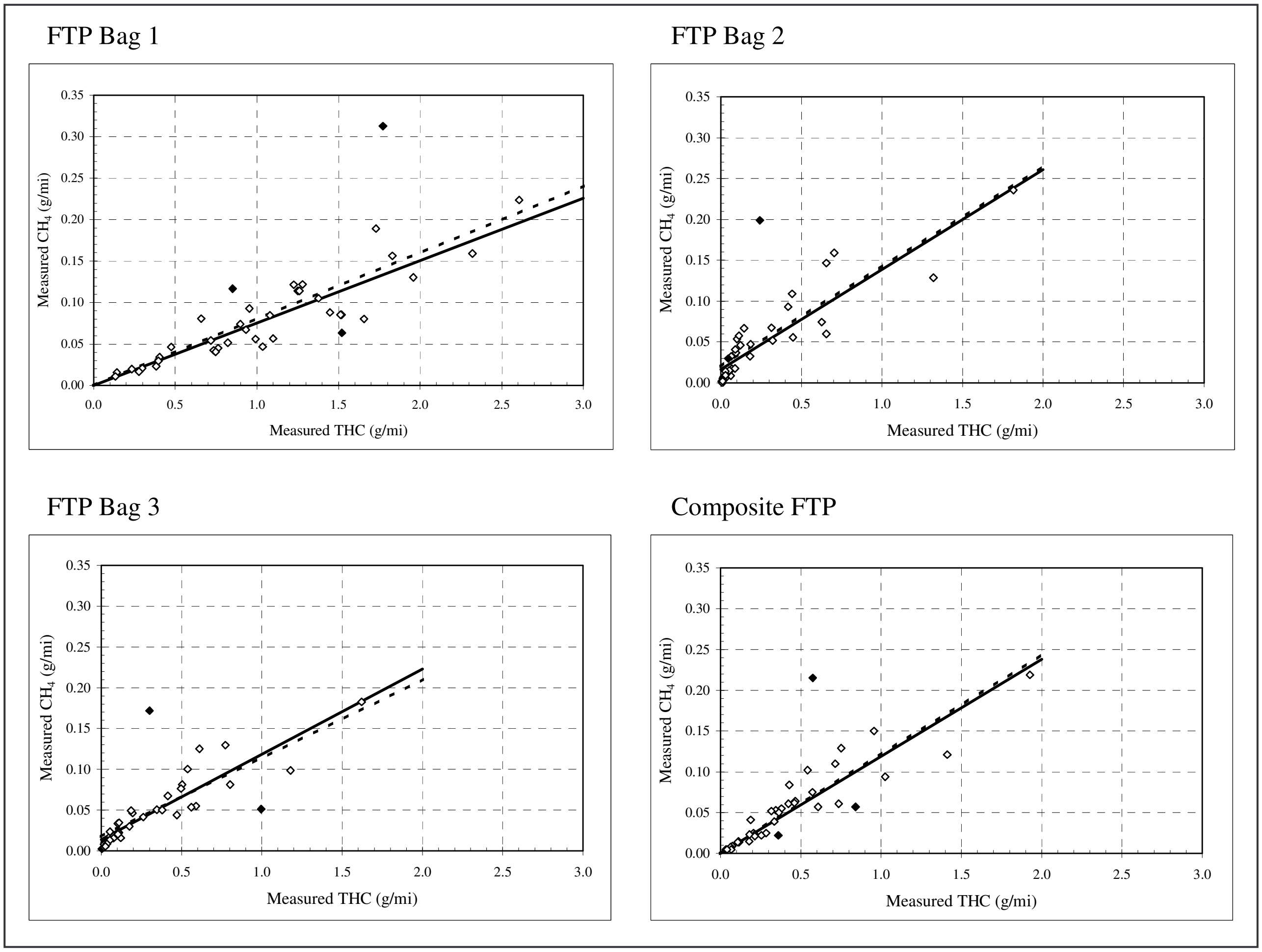


Note: Solid markers indicate data for 1993 and newer vehicles, open markers indicate data for 1992 and older vehicles. The sloping solid line is a simple linear trendline that is not used for any specific purpose other than to determine the general year-to-year rate of mileage change (6,640 miles). The dashed lines indicate the mileage bounds applied to a secondary data analysis described in detail below.

Table E-1: Summary Descriptive Data for Vehicles in the ARB VSP Dataset

Model Year	Vehicle Make	Vehicle Model	Disp (liters)	Odometer (miles)	Vehicle Class
1981	Chevrolet	Van 20	5.0	140,642	MDV
1983	Chevrolet	Caprice Classic Station Wagon	5.0	129,370	PC
1984	Volvo	DL 4-Door	2.3	140,508	PC
1985	Chevrolet	Blazer	2.8	101,625	LDT1
1986	Saab	900	2.0	153,916	PC
1986	Cadillac	El Dorado Biarritz	4.1	64,505	PC
1986	Toyota	Camry LE	2.0	326,358	PC
1986	Mercury	Capri GS	3.8	68,251	PC
1987	Cadillac	El Dorado 2-Door	4.1	172,416	PC
1988	Toyota	Corolla FX	1.6	97,947	PC
1989	Chevrolet	Geo Metro LSi	1.0	163,882	PC
1989	Toyota	Tercel Hatchback	1.5	234,588	PC
1990	Nissan	Pathfinder XEV6	3.0	153,896	LDT2
1991	Pontiac	Transport	3.1	124,716	LDT2
1991	Chrysler	Lebaron LE	3.0	94,121	PC
1991	Cadillac	Sedan DeVille	4.9	53,804	PC
1992	Pontiac	Grand Am 4-Door	3.3	88,497	PC
1993	Cadillac	Sedan DeVille 4-Door	4.9	101,147	PC
1993	Mercury	Villager GS	3.0	123,070	LDT2
1993	Toyota	Corolla	1.6	162,332	PC
1993	Nissan	Sentra XE	1.6	78,016	PC
1993	Toyota	Camry LE 4-Door	2.2	89,252	PC
1993	Acura	Integra LS 3-Door	1.8	81,987	PC
1994	Ford	Taurus GL 4-Door	3.0	51,773	PC
1994	Toyota	Camry XLE	3.0	110,134	PC
1995	Chevrolet	Geo Prism LSi	1.6	118,082	PC
1995	Plymouth	Neon 4-Door	2.0	63,752	PC
1995	Toyota	Camry LE	2.2	78,773	PC
1996	Dodge	Ram 1500	5.2	116,400	MDV3
1996	Mazda	626 LX	2.0	104,185	PC
1996	Toyota	Camry LE	2.2	49,631	PC
1997	Ford	Expedition XLT	4.6	73,598	MDV3
1997	Mazda	Miata	1.8	65,733	PC
1998	Dodge	Neon 4-Door	2.0	76,375	PC
1999	Ford	Taurus SE	3.0	69,617	PC
2000	Volkswagen	GTI Turbo	1.8	31,959	PC
2000	Toyota	4Runner 2WD	2.7	39,252	LDT2
2000	Saturn	Saturn SL 4-Door	1.9	31,973	PC
2001	Ford	Taurus LS	3.0	1,724	PC

Figure E-2: CH_4 Emission Rate Versus THC Emission Rate



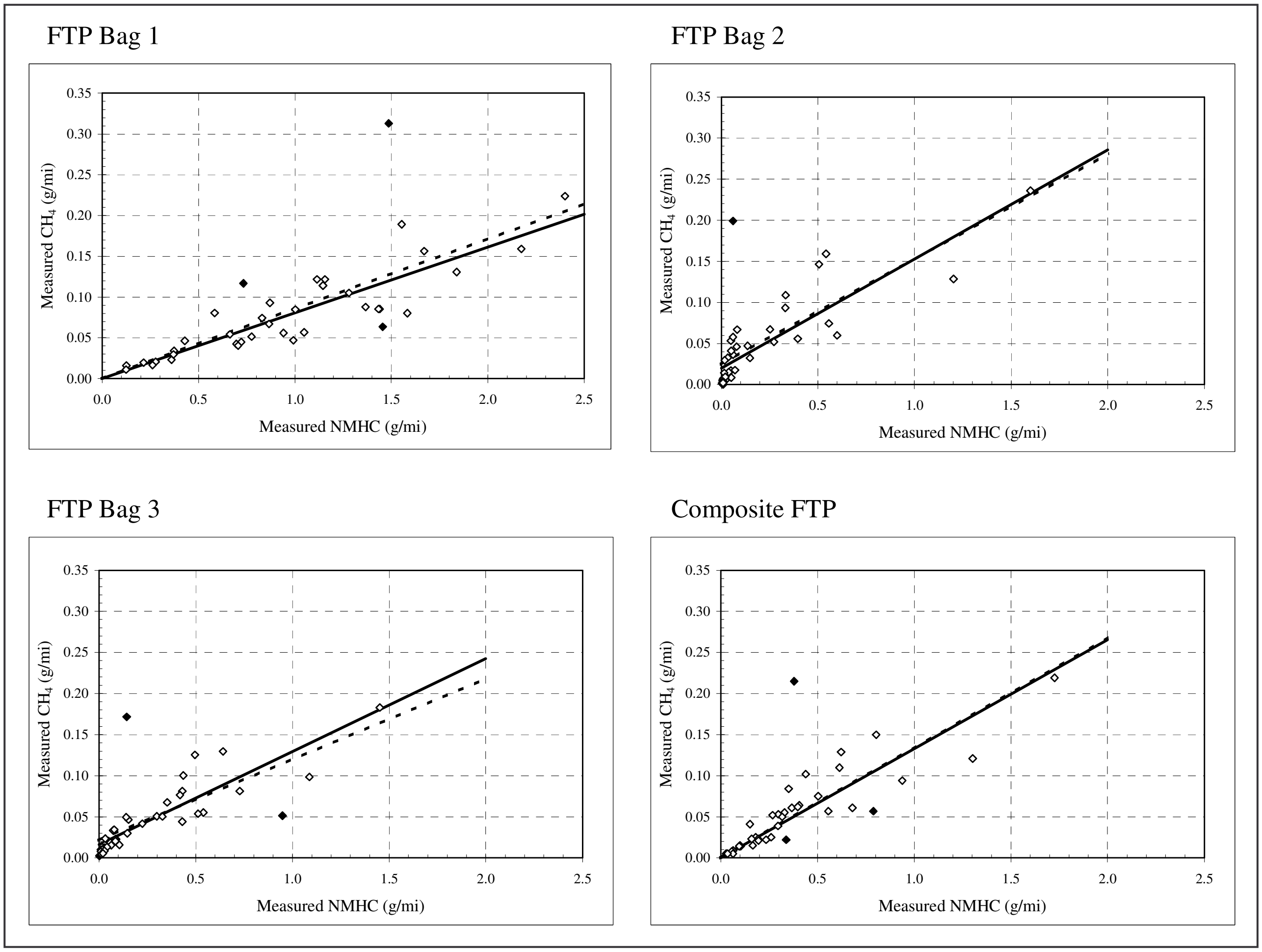
Note: The dotted and solid lines indicate regression-based relations. Dotted lines include all data, solid lines exclude outliers (defined as datapoints that vary from the average CH_4/THC or THC/CH_4 ratio by more than two standard deviations).

Table E-2: Regression Statistics for CH_4 (g/mi) Versus THC (g/mi)

Statistic	All Data				Outliers (±2σ) Removed			
	Bag 1	Bag 2	Bag 3	Composite	Bag 1	Bag 2	Bag 3	Composite
Intercept	0.0000	0.0201	0.0175	0.0000	0.0000	0.0165	0.0137	0.0000
Slope	0.0803	0.1227	0.0963	0.1220	0.0753	0.1223	0.1047	0.1190
r^2	0.64	0.67	0.62	0.67	0.83	0.82	0.84	0.86
n (obs)	39	39	39	39	36	36	35	36

Slope and intercept statistics are selected at 95 percent confidence level.

Figure E-3: CH_4 Emission Rate Versus NMHC Emission Rate



Note: The dotted and solid lines indicate regression-based relations. Dotted lines include all data, solid lines exclude outliers (defined as datapoints that vary from the average CH_4/NMHC or NMHC/CH_4 ratio by more than two standard deviations).

Table E-3: Regression Statistics for CH_4 (g/mi) Versus NMHC (g/mi)

Statistic	All Data				Outliers (±2σ) Removed			
	Bag 1	Bag 2	Bag 3	Composite	Bag 1	Bag 2	Bag 3	Composite
Intercept	0.0000	0.0248	0.0213	0.0000	0.0000	0.0201	0.0160	0.0000
Slope	0.0857	0.1282	0.0986	0.1342	0.0806	0.1328	0.1132	0.1326
r^2	0.59	0.57	0.54	0.58	0.80	0.76	0.80	0.82
n (obs)	39	39	39	39	36	37	35	36

Slope and intercept statistics are selected at 95 percent confidence level.

The relationship between measured methane and measured THC emission rates, as well as the relationship between measured methane and measured NMHC emission rates, was investigated. Figure E−2 and Table E−2 present the results of the THC analysis, while Figure E−3 and Table E−3 present the results of the NMHC analysis. As expected, statistically significant relations between both CH_4 and THC and CH_4 and NMHC were found (of course, a valid relation for either implies a valid relation for the other). As shown in Tables E−2 and E−3, valid relations exist for all three bags of the FTP, but the CH_4 fraction of HC increases in Bag 2. This is expected since Bag 2 reflects hot stabilized catalyst operation, wherein NMHC conversion efficiencies will be at their maximum. Although CH_4 conversion will also increase in Bag 2, efficiency will generally be below the peak efficiencies for NMHC due to the decreased reactivity of methane.

As shown in Table E-2, methane generally constitutes about 7.5 to 12 percent of THC emissions, with the smaller fractions being observed in Bags 1 and 3 of the FTP, during which the catalyst has not yet attained peak conversion conditions and NMHC emissions are highest.[53] Relative to NMHC, Table E-3 shows that the methane emission rate generally ranges from 8 to 13 percent of that for NMHC. This is in good agreement with algebraic expectations, where a 10± percent increase in emissions fraction would be expected in moving the relationship base from THC to NMHC.[54] From a composite emissions standpoint,

$$CH_4 = 0.119\ (THC)$$

or

$$CH_4 = 0.133\ (NMHC)$$

Assuming the THC coefficient to be precise, the algebraic NMHC equivalent coefficient would be 0.135 (0.119/(1-0.119)). This varies from the regression-based coefficient by less than 2 percent, so the independent regression analysis results are quite consistent.

As indicated by the VSP data, as THC (and NMHC) is reduced, methane is also reduced in a proportional manner. Thus, as vehicle technology advances to meet stricter organic compound emission standards, it is reasonable to expect that methane emissions will also decline. However, since it could be possible to derive similar relationships from data for equivalently emitting vehicles tested at different mileage accumulations throughout their deterioration cycle, a secondary analysis was performed to ensure that this was not the case with the VSP data.

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53 Note that both Tables Q-2 and Q-3 include “All Data” and “Outliers Removed” statistics. The former includes data for all 39 dataset vehicles. The latter excludes data for vehicles with either CH_4/X or X/CH_4 ratios that vary from the average ratio by more than ±2 standard deviations, where X indicates the independent parameter (i.e., either THC or NMHC). Data identified as outliers are indicated in Figures Q-2 and Q-3 as solid markers.

54 If $CH_4/THC = x$ and $CH_4/NHMC = y$, then $y = CH_4/(THC-CH_4) = CH_4/(THC-THC(x)) = CH_4/(THC(1-x)) = x/(1-x)$. So if $x \cong 0.10$, then $y = 0.11 \cong 1.1x$.

In this secondary analysis, the VSP data were split into two component datasets, one for 1992 and earlier vehicles (17 vehicles) and one for 1993 and newer vehicles (22 vehicles). This split was selected on the basis that organic compound emission standards generally shifted in stringency beginning in 1993 when the first Tier 1 vehicles were required to be sold in California. Light duty vehicles from model years 1981 through 1992 were certified to Tier 0 emission standards. Organic compound emission standards continued to evolve throughout the 1990s as differing numbers of LEV vehicles were sold, but the VSP dataset analyzed for this study does not contain sufficient information to pinpoint the certification class of each vehicle. Nevertheless, there is no question that a split based on the 1993 model year is biased toward Tier 0 vehicles on the pre-1993 side and Tier 1/LEV vehicles on the 1993 and newer side. Thus, there is a clear distinction between the relative emissions control design of the two data subsets.[55]

Table E-4 indicates the results of the data subset analysis. To factor out the influence of mileage accumulation to the maximum extent possible, statistics were calculated on a stratified basis by 50,000 mile increment mileage accumulation bins. Statistics were then compared across the two samples only when five or more datapoints were present in comparable mileage bins. This results in comparisons for two mileage bins, 50,000-100,000 miles and 100,000-150,000 miles. As indicated, the 1993 and newer vehicle organic emissions have generally declined by 50 to 70 percent for THC, NMHC, *and* CH_4 relative to comparable mileage 1992 and older vehicles. To truly confirm the lack of mileage bias, a comparison of the 100,000-150,000 mile data for 1993 and newer vehicles to the 50,000-100,000 mile data for 1992 and older vehicles indicates that the *minimum* reduction in THC, NMHC, *and* CH_4 emission rates is between 30 and 50 percent, with the 50 percent reduction being applicable to methane. Clearly, methane emissions have declined between the two periods, while methane-to-THC and methane-to-NMHC ratios have remained relatively stable as described above. Therefore, it should be possible to estimate both current and future certification emission rates for methane on the basis of the derived relations.

Using the CH_4-to-NMHC regression results and U.S. light duty vehicle certification standards for NMOG, the methane emission rates for current and future vehicles were estimated. Since the regression relations are based on NMHC emissions, as opposed to NMOG emissions, the NMOG standards were converted to NMHC equivalent standards using the allowable certification adjustment factor of 1.04 as specified in the Code of Federal Regulations.[56] A certification compliance margin of 30 percent was also assumed, consistent with assumptions utilized for the CO_2 emissions analysis portion of the study. So in effect, the target NMHC emission rate for a given NMOG standard is equal to:

$$\text{Target NMHC} = \left[\frac{\text{NMOG Standard}}{1.04}\right] \times 0.70$$

[55] Despite the seeming clarity of this distinction, t-tests were conducted for the two samples. This testing indicates that the probability of the two samples being from the same population is <0.1 percent for THC, NMHC, and CH_4.

[56] 40 CFR §86.1810-01(p) allows NMOG emissions to be estimated as NMHC emissions times 1.04.

For Tier 1 standards, which were expressed in terms of NMHC, the NMOG adjustment was not performed. For Tier 0 standards, which were expressed in terms of THC, the NMOG adjustment was similarly not performed and the NMHC portion of THC was estimated using the Tier 0 NMHC-to-THC standard ratio developed by the U.S. Environmental Protection Agency (EPA) for natural gas vehicles (0.34/0.41).[57] Estimated methane emission rates were then developed on the basis of the previously described regressions as:

$$CH_4 = 0.133 \text{ (Target NMHC)}$$

The resulting emission rates are presented in Table E-5. As indicated, estimated emission rates range from 0.039 g/mi for a Tier 0 passenger car to 0.010 g/mi for a 2002 "fleet average" NLEV vehicle. Perhaps the best indication of the accuracy of these estimated emissions can be gleaned from a comparison of the estimated Tier 1 passenger car emission rate of 0.029 g/mi to the estimated 100,000 mile methane emission rate for 1993 and newer vehicles from the ARB VSP dataset used to develop the CH4 to NMHC regression relations. Although the 1993 and newer vehicles in the ARB dataset are likely to reflect a mix of LEV I and Tier 1 vehicles, the fleet average LEV standard for NMOG was dominated by Tier 1 vehicles through the late 1990s. Thus, it is reasonable to expect that the ARB dataset for 1993 and newer vehicles is similarly dominated by Tier 1 vehicles. In fact, a basic regression analysis of these data indicate an expected 100,000 mile methane emission rate of 0.034 g/mi, which compares well with the certification estimated rate for Tier 1 vehicles of 0.029 g/mi. As a result, it seems likely that the estimated methane emission rates presented in Table E 5 provide a reasonably accurate depiction of current and future emissions.

[57] Because natural gas vehicles have inherently higher methane emission rates than gasoline vehicles, the EPA established an equivalent stringency Tier 0 standard for natural gas vehicles in terms of NMHC. A standard of 0.31 g/mi NMHC was determined to be equivalent to the 0.41 g/mi Tier 0 THC standard for gasoline vehicles.

Table E-4: Average Hydrocarbon Emission Rates for Split VSP Database

Organic Species	Odometer (miles)	Pre-1993 Vehicles		1993 and Newer Vehicle		Percent Change (a)
		Average Emission Rate (g/mi)	Number of Observations	Average Emission Rate (g/mi)	Number of Observations	
THC	0-50,000		0	0.115	5	
	50,000-100,000	0.464	6	0.223	10	-52%
	100,000-150,000	0.943	5	0.314	6	-67%
	150,000-200,000	0.823	4	0.335	1	
	200,000-250,000	0.714	1		0	
	250,000-300,000		0		0	
	300,000-350,000	0.461	1		0	
	All Data	**0.704**	**17**	**0.228**	**22**	**-68%**
	50,000-150,000	**0.682**	**11**	**0.257**	**16**	**-62%**
NMHC	0-50,000		0	0.106	5	
	50,000-100,000	0.381	6	0.200	10	-47%
	100,000-150,000	0.830	5	0.271	6	-67%
	150,000-200,000	0.750	4	0.296	1	
	200,000-250,000	0.613	1		0	
	250,000-300,000		0		0	
	300,000-350,000	0.398	1		0	
	All Data	**0.614**	**17**	**0.202**	**22**	**-67%**
	50,000-150,000	**0.585**	**11**	**0.227**	**16**	**-61%**
CH_4	0-50,000		0	0.009	5	
	50,000-100,000	0.089	6	0.024	10	-73%
	100,000-150,000	0.120	5	0.044	6	-63%
	150,000-200,000	0.079	4	0.039	1	
	200,000-250,000	0.110	1		0	
	250,000-300,000		0		0	
	300,000-350,000	0.062	1		0	
	All Data	**0.095**	**17**	**0.027**	**22**	**-72%**
	50,000-150,000	**0.103**	**11**	**0.032**	**16**	**-69%**

Notes: (a) Only stratifications with five or more component datapoints are included.

Table E-5: Estimated Methane Emission Rates

Certification Level	NMOG Standard (g/mi)	NMHC Target (g/mi)	Predicted CH_4 (g/mi)	CO_2 Equivalent (g/mi)	Change from PC Tier 0	Change from PC Tier 1	Change from 02 NLEV
Tier 2,Bin 1/ZEV	0.000	0.000	0.000	0.000	-100%	-100%	-100%
Tier 2,Bin 2/SULEV	0.010	0.007	0.001	0.021	-98%	-97%	-91%
Tier 2,Bin 3/ULEV I/ULEV II	0.055	0.037	0.005	0.113	-87%	-83%	-50%
Tier 2,Bin 4	0.070	0.047	0.006	0.144	-84%	-78%	-37%
Tier 2,Bin 5/LEV I/LEV II	**0.090**	**0.061**	**0.008**	**0.185**	**-79%**	**-72%**	**-19%**
Tier 2,Bin 6	0.090	0.061	0.008	0.185	-79%	-72%	-19%
Tier 2,Bin 7	0.090	0.061	0.008	0.185	-79%	-72%	-19%
Tier 2,Bin 8	0.125	0.084	0.011	0.257	-71%	-61%	+13%
TLEV	0.156	0.105	0.014	0.320	-64%	-52%	+41%
Passenger Car Tier 1	0.310	0.217	0.029	0.662	-26%	0%	+191%
Passenger Car Tier 0	0.422	0.295	0.039	0.900	0%	+36%	+296%
2002 NLEV Fleet Average	0.111	0.075	0.010	0.227	-75%	-66%	0%
2002 LEV Fleet Average	0.101	0.068	0.009	0.207	-77%	-69%	-9%
2010 LEV Fleet Average	0.050	0.034	0.004	0.103	-89%	-85%	-55%

Notes: (1) For NMOG standards, the equivalent NMHC standard equals the NMOG standard divided by 1.04.
(2) For all fleet average standards, passenger car and LDT1/2 standards are weighted by 55 percent and LDT3/4 standards are weighted by 45 percent on the basis of the 2009 Martec market forecast described in Chapter 2 of the study report. Basically, the entire large truck and minivan classes are assumed to be LDT3/4, as is 60 percent of the small truck class.
(3) The target emissions level is 70 percent of the applicable standard.
(4) Predicted CH_4 equals the target NMHC emissions times 0.133.
(5) CO_2 equivalent emissions equal CH_4 emissions times 23 (the GWP of CH_4).

Table E-5 also indicates that by 2009, methane emissions can be expected to decline by about 19 percent, to 0.008 g/mi (about 0.2 g/mi CO_2 equivalent), from the estimated 2002 fleet average emission rate of 0.010 g/mi. This reduction will come about due to the imposition of the Tier 2 program and the improved combustion and aftertreatment efficiencies it is expected to promote. Since the Tier 2 program is already adopted, the incremental costs that will accrue to capture this methane reduction benefit are already accounted for under the Tier 2 program and thus no additional cost is incurred from a GHG perspective. As is also indicated, it is possible to promote further methane reductions through even further advances in combustion and aftertreatment efficiency. However, since the total expected CO_2 equivalent emission rate in 2009 is less than 0.2 g/mi, the overall GHG reduction potential is quite limited. For example, adding advanced technology required to certify vehicles to the Tier 2, Bin 3 level will reduce emissions by another 40 percent, but this translates into an absolute CO_2 equivalent reduction of less than 0.1 g/mi. Technology capable of meeting Tier 2, Bin 2 levels will increase the added reduction to almost 90 percent, with the absolute reduction increasing to about 0.15 g/mi CO_2 equivalent.

As additional emission reduction potential is clearly occurring "at the margin" due to already low methane emission rates, the cost effectiveness of additional reductions is relatively high. In developing the NLEV program, the EPA estimated the incremental retail cost of a ULEV I vehicle relative to a LEV I vehicle at $30. [8] This estimate properly reflects the technology required to reduce NMOG emissions from Tier 2, Bin 5 levels to Tier 2, Bin 3 levels while holding NO_x control constant, and is generally consistent with similar cost impacts estimated by the ARB. [9] As indicated in Table E-6, this implies a cost effectiveness of about $2,500 per ton of equivalent CO_2 reduction, *assuming all associated costs are attributed to methane reduction*.

ARB estimates for the incremental retail cost of a SULEV vehicle relative to a ULEV II vehicle provide similar insight into the cost effectiveness of controlling methane to the Tier 2, Bin 2 level. These costs are estimated at about $70 per vehicle after correcting for the increased rhodium loading estimated to be needed for reducing ULEV II NO_x to SULEV levels. [10] This implies a cost effectiveness of about $3,700 per ton of equivalent CO_2 for reducing methane from Tier 2, Bin 5 to Tier 2, Bin 2 levels, or a marginal cost effectiveness of about $4,600 per ton of equivalent CO_2 for reducing methane from Tier 2, Bin 3 levels. Of course, reductions of NMOG also accrue, which could be used to offset a portion of the imposed cost. Since methane reductions accrue in proportion to NMOG reductions, it seems most logical to consider future methane reduction as an integral component of Tier 2 and LEV II program reviews. This would maintain a consistent approach to continued program development, while properly reflecting both the criteria and GHG emission benefits of such programs.

It is also important to note that the methane relationships presented in this study are derived from data for stoichiometric control technology. Existing research indicates that, unlike NMHC conversion, the methane conversion efficiency of typical stoichiometric three-way catalysts falls off fairly rapidly at lean conditions. [11] This is likely due to the reduced exhaust temperatures associated with lean combustion and, as a result, methane emissions for combustion technologies such as lean gasoline direct injection and diesel may need to be investigated further as detailed research data become available. At the same time, it is also likely that the excess air combustion

Table E-6: Cost and Cost Effectiveness of Methane Reductions

Reduction Strategy	CH_4 Change (g/mi)	CO_2 Equivalent Change (g/mi)	Marginal Cost	Cost Effectiveness ($/ton CO_2)
Tier 2,Bin 5 to Tier 2, Bin 3	0.003	0.072	$ 30	$ 2,526
Tier 2,Bin 5 to Tier 2, Bin 2	0.007	0.164	$ 100	$ 3,683
Tier 2,Bin 3 to Tier 2, Bin 2	0.004	0.092	$ 70	$ 4,584

Notes: (1) Cost effectiveness is based on a lifetime mileage estimate of 150,000 miles.

associated with such technologies will produce lower engine-out methane emissions than is the case with stoichiometric technology, but this should be confirmed during certification testing.

In the absence of specific data on advanced lean burn technology, this study relies on an estimated methane emission rate derived from the EPA's MOBILE6.2 emission factor model for light duty diesel passenger cars and trucks. [15] The EPA model was executed for two evaluation years, 2002 and 2009, and methane emission rates were calculated as the difference between model-estimated THC and NMHC emission rates. The resulting methane emission rate, 0.005 g/mi, was identical for both evaluation years and is, in a general sense, quite consistent with the emission rates presented in Table E-5 for stoichiometric technology. An emission rate of this magnitude certainly reflects inherently low methane emissions, given that it is equivalent to emissions associated with highly advanced aftertreatment technology (i.e., Tier 2, Bin 3 technology). Moreover, the emission rate also appears to be reasonably consistent with the methane emission rates of larger diesel engines as measured in several emissions test programs. For example, a test program conducted by the Center for Environmental Research and Technology at the University of California-Riverside found the average methane emission rate of fifteen 1982 though 1996 light and medium heavy duty diesel vehicles to be 0.011 g/mi. [16] Therefore, in the absence of more representative test data, a lean burn emission rate of 0.005 g/mi has been assumed for this study.

E.3. Nitrous Oxide Emissions

As indicated in Section E.1, N_2O is emitted from light duty vehicles due to the incomplete reduction of engine-out NO_x emissions in current catalytic aftertreatment systems. However, as was the case with methane emissions, it is important to recognize that current vehicles produce and emit substantially less N_2O than their older counterparts. Moreover, even in the absence of additional regulation, it is almost certain that future vehicles will exhibit even lower emission rates. Although there are currently no specific standards that directly limit emissions of N_2O, existing standards for NO_x do effectively result in reduced N_2O emissions through the design and implementation of advanced combustion and catalyst technologies.

Although the existing body of research on N_2O emissions is somewhat limited, available research does provide for a basic theoretical understanding of the N_2O formation process that is consistent with available test data. At low catalyst temperatures, NO_x reduction by carbon monoxide (CO) is believed to proceed according to the following pathway:[58] [3,4]

$$2NO + CO \rightarrow N_2O + CO_2$$
$$N_2O + CO \rightarrow N_2 + CO_2$$

As indicated, N_2O is formed as an intermediate reaction product, which can be emitted due to low temperature inefficiencies in carrying out the subsequent dissociation

[58] The indicated reactions are simplified depictions of a more complex catalytic reaction process, but they effectively present the important elements of the N_2O formation process.

reaction. The N_2O formation reaction appears to dominate up to about 300ºC. At higher catalyst temperatures, N_2O formation ceases as the NO_x reduction reaction proceeds in accordance with the single step reaction:

$$2NO + CO \rightarrow N_2 + CO_2$$

Thus, N_2O formation is primarily a function of catalyst warmup. This has been confirmed through several research testing programs that clearly show N_2O formation rates peaking during vehicle start-up operations as the aftertreatment catalyst moves through its warm up stage. In effect, measured FTP emissions of N_2O are dominated by emissions during Bag 1 and Bag 3 of the driving cycle. [3,4,12]

Of course, the same dominance of Bag 1 and 3 emissions would occur for an engine-out exhaust species undergoing inefficient conversion due to low catalyst temperatures. However, several test programs have demonstrated that engine-out N_2O emissions are consistent with background N_2O concentrations, so that there is little uncertainty but that N_2O emissions are formed within the aftertreatment catalyst and not within the vehicle engine. [3-6] At the same time, it should be recognized that N_2O can form within the combustion chamber through reactions with intermediate combustion products such as:

$$HN + NO \rightarrow N_2O + H$$
$$HCO + NO \rightarrow N_2O + CO$$

However, such N_2O is also rapidly removed to create OH radicals:

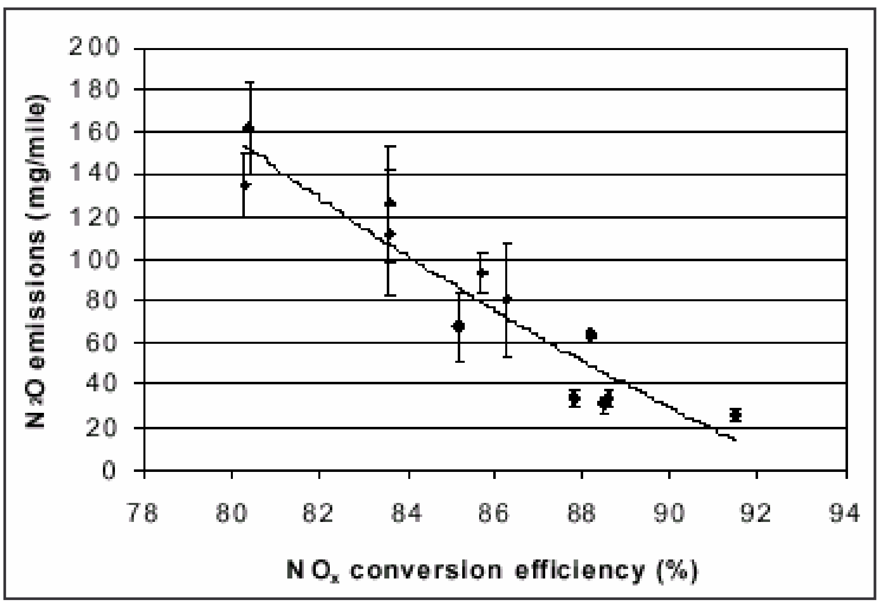
$$N_2O + H \rightarrow N_2 + OH$$

so that engine-out N_2O is very low. [3]

Given the demonstrated formation mechanism, it is widely believed that the control of vehicle N_2O emissions is a function of improved aftertreatment systems. As was the case with organic compounds (see Section E.2), emissions control of NO_x (and thus NO) has evolved over the years. Both advanced engine technologies and improved catalytic aftertreatment techniques have reduced NO_x emissions to a fraction of that emitted by older vehicles. For example, a 2002 model year vehicle emits about 80 percent less NO_x than a 1981 era vehicle. By 2009, the reduction will increase to about 95 percent through continuing combustion and aftertreatment improvements. As was the case with methane, these improvements should result in decreases in N_2O emissions commensurate with increases in catalytic aftertreatment efficiency. As will be shown below, typical N_2O emissions are approaching levels associated with non-catalyst vehicles, but it is likely that a reasonable lower limit for N_2O emissions will continue to be greater than would be the case if catalytic aftertreatment systems were eliminated. Of course, associated increases in criteria pollutant emissions (i.e., HC, CO, and NO_x) due to catalyst removal would be several orders of magnitude larger than the net reduction in N_2O.

Expectations for continued N_2O reductions are consistent with existing research. In a review of N_2O emissions research, the EPA generally found that emission factors decline for three-way catalyst equipped vehicles as NO_x control efficiency increases. [13] Similarly, a recent test program conducted under rigorously controlled conditions across a set of controlled usage vehicles found a clear relationship between NO_x aftertreatment efficiency and N_2O emissions, as depicted in Figure E−4. [4] Nevertheless, to confirm this relationship, the 39 vehicle ARB VSP dataset previously described in Section E.2 above was utilized to estimate study-specific N_2O emission rates. [7] While 39 vehicles is certainly a limited dataset, it should be recognized that unlike methane, N_2O is generally not measured as part of the standard vehicle certification process in the U.S., so there is not an extensive library of available N_2O data. In fact, the VSP dataset includes approximately the same volume of N_2O emission rate data as all previous test programs combined. Moreover, it provides a snapshot of emissions from actual in-use vehicles.

Figure E-4: N_2O Emission Rate Versus NO_x Conversion Efficiency [4]



Since the VSP dataset was previously described in Section E.2, readers are referred to that section for additional background. Figure E−1 and Table E−1 of Section E.2 provide an overview of the vehicle fleet represented in the VSP dataset. For this study, the relationship between measured N_2O and measured NO_x emission rates was investigated. Figure E−5 and Table E−7 present the results of this analysis. As expected from the findings of previous researchers, statistically significant relations between N_2O and NO_x emissions were found. As shown in Table E−7, valid relations exist for all three bags of the FTP after outliers were removed.[59] When all data were considered, valid relationships were found for Bags 2 and 3, but not Bag 1. The lack of a Bag 1 relationship prior to the removal of outliers is the result of a single vehicle with very high

[59] Consistent with the methane analysis described in Section Q.2, outliers are identified as vehicles with either N_2O/NO_x or NO_x/N_2O ratios that vary from the average ratio by more than ±2 standard deviations. Data identified as outliers are indicated in Figure E−5 as solid markers.

NO_x and very low N_2O emissions (a carbureted 1981 Chevrolet Van with 5.1 g/mi NO_x and 0.02 g/mi N_2O). Data for this vehicle are consistent with very low aftertreatment efficiency, as N_2O emissions approach those of non-catalyst vehicles. This same vehicle was also identified as an outlier for both the Bag 3 and composite cycle analyses, but because N_2O emissions decline substantially for all vehicles during Bag 2, it was sufficiently consistent with the other VSP data for the Bag 2 analysis.

As shown in Table E−7, N_2O generally is emitted at a rate about 2 to 3 percent of the NO_x emission rate, except during the start portions of the FTP cycle (i.e., Bags 1 and 3) when an additional 0.02 to 0.03 g/mi is emitted. Over the full cycle, the N_2O emission rate is equal to about 3 percent of the NO_x emission rate plus 0.015 g/mi:

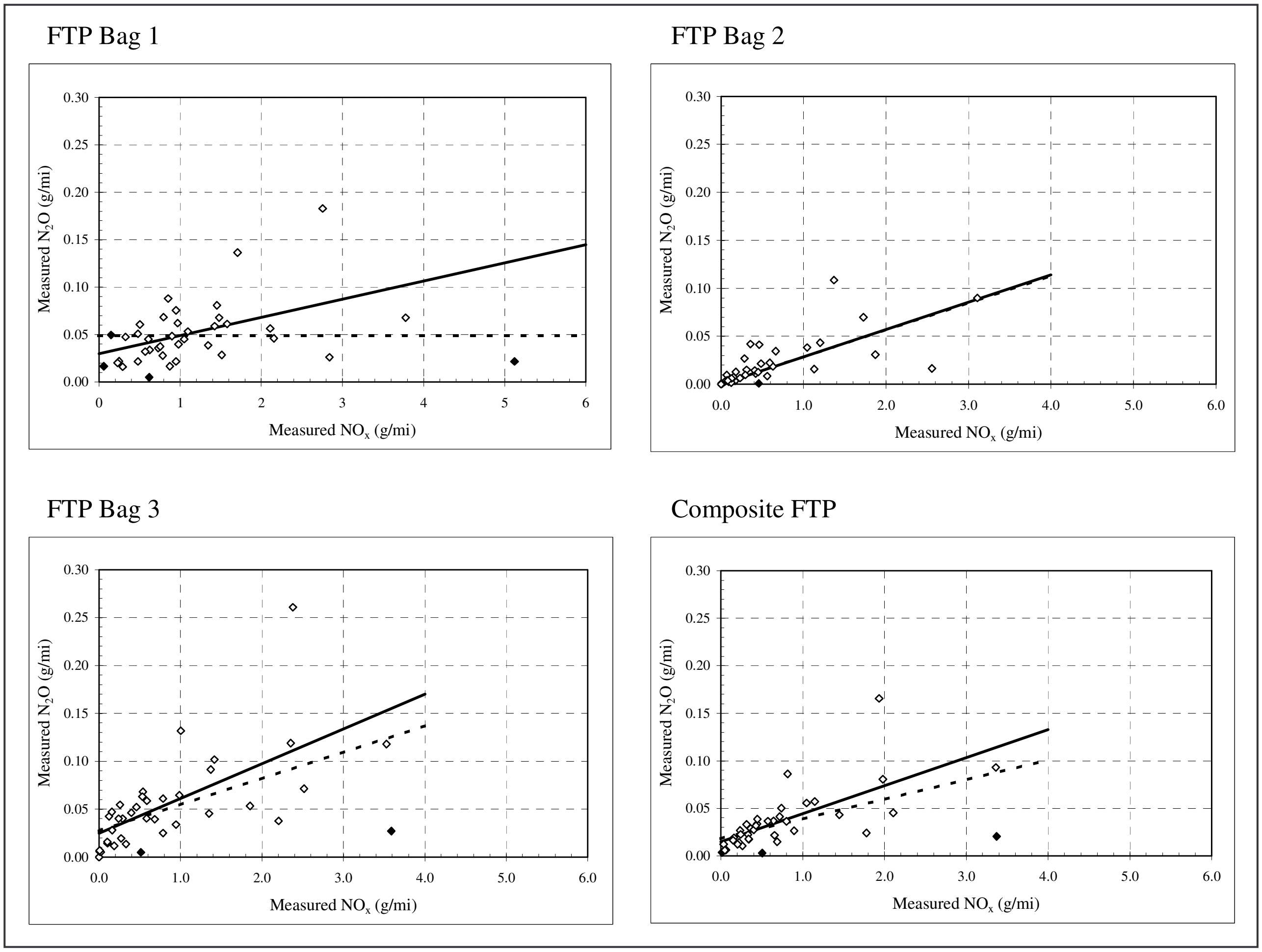
$$N_2O = 0.0295\,(NO_x) + 0.0150$$

Thus, as NO_x is reduced, N_2O is also reduced proportionally *to a lower limit of 0.015 g/mi*. Such a finding is quite consistent with previous research, where maximum N_2O formation occurs during catalyst warmup, from about 100ºC to 300ºC for new catalysts or 200ºC to 400ºC for aged catalysts.

Figure E−6 illustrates the sensitivity of N_2O formation to catalyst temperature. Since all catalysts will pass through the maximum N_2O formation temperature band after vehicle startup, there is a period of time during which N_2O emissions increase while NO_x declines (as NO is converted to N_2O). After the catalyst passes this band, both NO_x and N_2O conversion efficiencies increase and additional N_2O emissions are generally proportional to NO_x emissions. Thus, the volume of N_2O generated during initial catalyst warmup represents a practical lower limit for current three-way catalyst technology and N_2O reductions below this level will require significant advances in warmup characteristics.

Interestingly, the shift in the N_2O formation window to higher temperatures with catalyst aging results in a rather uncommon phenomenon relative to other emission species affected by catalyst aftertreatment. For aged catalysts, such as those represented in the ARB VSP dataset analyzed in this study, N_2O emissions during Bag 3 generally equal or exceed those of Bag 1. This is due to the fact that the shift upwards in the N2O formation temperature band can result in a somewhat longer period during Bag 3 (as compared to Bag 1) in which catalyst temperatures are within the band.

Figure E-5: N_2O Emission Rate Versus NO_x Emission Rate



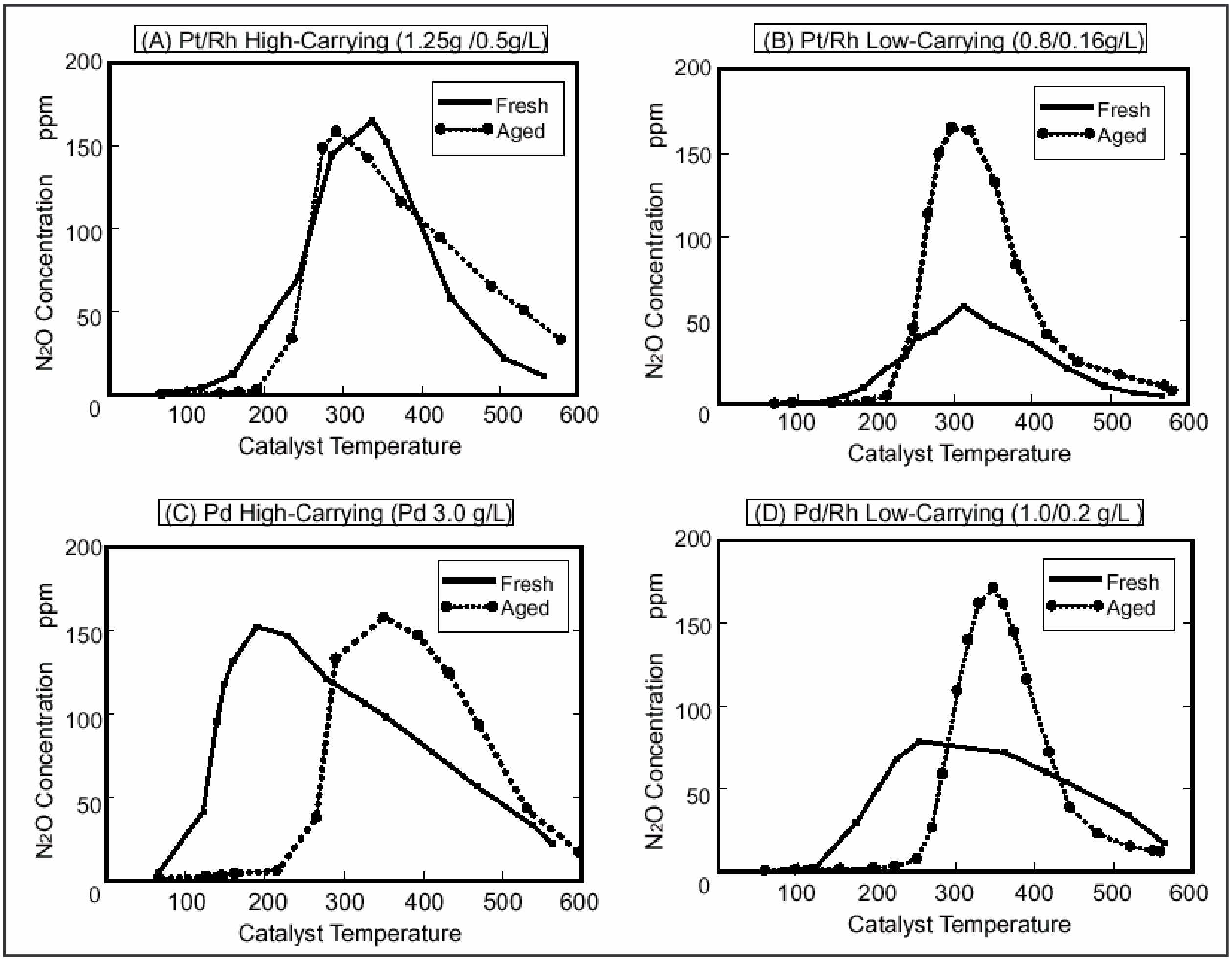
Note: The dotted and solid lines indicate regression-based relations. Dotted lines include all data, solid lines exclude outliers (defined as datapoints that vary from the average N_2O/NO_x or NO_x/N_2O ratio by more than two standard deviations).

Table E-7: Regression Statistics for N_2O (g/mi) Versus NO_x (g/mi)

Statistic	All Data				Outliers (±2σ) Removed			
	Bag 1	Bag 2	Bag 3	Composite	Bag 1	Bag 2	Bag 3	Composite
Intercept	0.0491	0.0000	0.0272	0.0183	0.0301	0.0000	0.0249	0.0150
Slope	0.0000	0.0283	0.0275	0.0207	0.0191	0.0285	0.0362	0.0295
r^2	0.00	0.46	0.31	0.32	0.21	0.45	0.43	0.48
n (obs)	39	39	39	39	35	37	35	35

Slope and intercept statistics are selected at 95 percent confidence level.

Figure E-6: N_2O Formation Rate Versus Catalyst Temperature [14]



As was the case with the methane analysis described in Section E.2, a secondary statistical analysis was conducted to ensure that the derived N_2O-to-NO_x relations were not simply a function of equivalently emitting vehicles measured at different mileage accumulations during their deterioration cycle. In this secondary analysis, the VSP data were split into two component datasets, one for 1992 and earlier vehicles (17 vehicles) and one for 1993 and newer vehicles (22 vehicles). As described in more detail in Section E.2, this split was selected on the basis of a general shift in emission standard stringency beginning in 1993 when the first Tier 1 vehicles were required to be sold in California.[60]

Table E−8 indicates the results of the data subset analysis. To factor out the influence of mileage accumulation to the maximum extent possible, statistics were calculated on a stratified basis by 50,000 mile increment mileage accumulation bins. Statistics were then compared across the two samples only when five or more datapoints

[60] T-tests indicate that the probability of the two samples being from the same population is about 0.2 percent for NO_x and about 3 percent for N_2O.

were present in comparable mileage bins. This results in comparisons for two mileage bins, 50,000-100,000 miles and 100,000-150,000 miles. As indicated, the 1993 and newer vehicle emissions have generally declined by 30 to 50 percent for N_2O and 50 to 60 percent for NO_x relative to comparable mileage 1992 and older vehicles. Clearly, N_2O emissions have declined between the two periods, while N_2O-to-NO_x ratios have remained relatively stable as described above. Therefore, it should be possible to estimate both current and future certification emission rates for N_2O on the basis of the derived regression relations.

Using the N_2O-to-NO_x regression results and U.S. light duty vehicle certification standards for NO_x, the N_2O emission rates for current and future vehicles were estimated. As with the methane analysis discussed in Section E.2, a certification compliance margin of 30 percent was assumed, consistent with assumptions utilized for the CO_2 emissions analysis portion of the study. So in effect, the target NO_x emission rate for a given NO_x standard is equal to:

$$\text{Target } NO_x = NO_x \text{ Standard} \times 0.70$$

Estimated N_2O emission rates were then developed on the basis of the previously described regression as:

$$N_2O = 0.0295\,(NO_x) + 0.0150$$

The resulting emission rates are presented in Table E-9. As indicated, estimated emission rates range from 0.046 g/mi for a Tier 0 passenger car to 0.021 g/mi for a 2002 “fleet average” NLEV vehicle. Perhaps the best indication of the accuracy of these estimated emissions can be gleaned from a comparison of the estimated Tier 1 passenger car emission rate of 0.027 g/mi to the estimated 100,000 mile N_2O emission rate for 1993 and newer vehicles from the ARB VSP dataset used to develop the N_2O-to-NO_x regression relations.[61] As described in Section E.2, the 1993 and newer vehicles in the ARB dataset are likely to reflect a mix of LEV I and Tier 1 vehicles, but the fleet average LEV requirements were such that Tier 1 vehicles were sold in substantial quantities through the late 1990s. Thus, it is reasonable to expect that the ARB dataset for 1993 and newer vehicles is similarly dominated by Tier 1 vehicles. In fact, a basic regression analysis of these data indicate an expected 100,000 mile N_2O emission rate of 0.029 g/mi, which compares well with the certification estimated rate of 0.027 g/mi.

The estimated N_2O emission rate for Tier 1 vehicles also compares favorably with emission rates estimated by the EPA. [13] As published, the EPA estimated N_2O emission rates for Tier 1 vehicles of 0.046 g/mi for passenger cars and 0.064 for light duty trucks appear to be much higher than the estimate of 0.027 g/mi from Table E-9. However, the EPA emission rates are for a 285 ppm sulfur gasoline, while those estimated in this study are for low sulfur California fuel.

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[61] Since the certification standards used to develop the estimated N_2O emission rate are 100,000 (or 120,000) mile standards, measured emissions at 100,000 miles are an appropriate comparison metric.

Table E-8: Average NO_x and N_2O Emission Rates for Split VSP Database

Organic Species	Odometer (miles)	Pre-1993 Vehicles		1993 and Newer Vehicle		Percent Change (a)
		Average Emission Rate (g/mi)	Number of Observations	Average Emission Rate (g/mi)	Number of Observations	
NO_x	0-50,000		0	0.098	5	
	50,000-100,000	0.709	6	0.339	10	-52%
	100,000-150,000	1.901	5	0.747	6	-61%
	150,000-200,000	1.548	4	0.444	1	
	200,000-250,000	0.688	1		0	
	250,000-300,000		0		0	
	300,000-350,000	0.801	1		0	
	All Data	**1.261**	**17**	**0.400**	**22**	**-68%**
	50,000-150,000	**1.251**	**11**	**0.492**	**16**	**-61%**
N_2O	0-50,000		0	0.009	5	
	50,000-100,000	0.035	6	0.025	10	-29%
	100,000-150,000	0.065	5	0.033	6	-50%
	150,000-200,000	0.056	4	0.039	1	
	200,000-250,000	0.015	1		0	
	250,000-300,000		0		0	
	300,000-350,000	0.036	1		0	
	All Data	**0.048**	**17**	**0.024**	**22**	**-49%**
	50,000-150,000	**0.049**	**11**	**0.028**	**16**	**-43%**

Notes: (a) Only stratifications with five or more component datapoints are included.

As described further below, sulfur has been shown to have a significant influence on N_2O emission rates, as might be expected given its detrimental influence on catalyst efficiency. Thus, the EPA emission rates are not directly comparable with those estimated in this study. The EPA did, however, test two Tier 1 vehicles on both the 285 ppm sulfur gasoline and indolene containing 24 ppm sulfur. The results of this comparative testing showed that N_2O emission rates were reduced by 28 and 49 percent on the low sulfur fuel.[62] While this is certainly a limited test sample, it does indicate that the EPA estimated N_2O emission rates, when corrected for fuel sulfur content, are more likely within a range of 0.024 to 0.046 g/mi, which is reasonably consistent with the 0.027 g/mi emission rate estimated in this study. As a result, it seems likely

[62] One Tier 1 vehicle had measured N_2O emission rates of 0.039 g/mi with 24 ppm sulfur and 0.054 g/mi with 285 ppm sulfur, for a net emission rate reduction of 28 percent. The second Tier 1 vehicle had measured N_2O emission rates of 0.115 g/mi with 24 ppm sulfur and 0.227 g/mi with 285 ppm sulfur, for a net emission rate reduction of 49 percent.

Table E-9: Estimated N_2O Emission Rates

Certification Level	NO_x Standard (g/mi)	NOx Target (g/mi)	Predicted N_2O (g/mi)	CO_2 Equivalent (g/mi)	Change from PC Tier 0	Change from PC Tier 1	Change from 02 NLEV
Tier2,Bin 1/ZEV	0.000	0.000	0.015	4.4	-67%	-45%	-28%
Tier2,Bin 2/SULEV	0.020	0.014	0.015	4.6	-66%	-44%	-26%
Tier2,Bin 3	0.030	0.021	0.016	4.6	-66%	-43%	-25%
Tier2,Bin 4	0.040	0.028	0.016	4.7	-66%	-42%	-24%
Tier2,Bin 5/LEV II/ULEV II	**0.070**	**0.049**	**0.016**	**4.9**	**-64%**	**-40%**	**-21%**
Tier2,Bin 6	0.100	0.070	0.017	5.0	-63%	-38%	-18%
Tier2,Bin 7	0.150	0.105	0.018	5.4	-61%	-34%	-13%
Tier2,Bin 8	0.200	0.140	0.019	5.7	-58%	-30%	-8%
LEV I/ULEV I	0.300	0.210	0.021	6.3	-54%	-23%	+2%
PC Tier 1/TLEV	0.600	0.420	0.027	8.1	-40%	0%	+32%
PC Tier 0	1.500	1.050	0.046	13.6	0%	+68%	+122%
2002 NLEV Fleet Average	0.276	0.193	0.021	6.1	-55%	-24%	0%
2002 LEV Fleet Average	0.262	0.183	0.020	6.0	-56%	-25%	-1%
2010 LEV Fleet Average	0.061	0.043	0.016	4.8	-65%	-41%	-21%

Notes: (1) For all fleet average standards, passenger car and LDT1/2 standards are weighted by 55 percent and LDT3/4 standards are weighted by 45 percent on the basis of the 2009 Martec market forecast described in Chapter 2 of the study report. Basically, the entire large truck and minivan classes are assumed to be LDT3/4, as is 60 percent of the small truck class.
(2) The target emissions level is 70 percent of the applicable standard.
(3) Predicted N_2O equals the target NO_x emissions times 0.0295 plus 0.0150.
(4) CO_2 equivalent emissions equal N_2O emissions times 296 (the GWP of N_2O).

that the N_2O emission rates estimated in this study provide for a reasonably accurate depiction of current and future emissions.

Table E-9 indicates that by 2009, N_2O emissions can be expected to decline by about 21 percent, to 0.016 g/mi (about 4.9 g/mi CO_2 equivalent), from the estimated 2002 fleet average emission rate of 0.021 g/mi. This reduction will come about due to the imposition of the federal Tier 2 program and the improved combustion and aftertreatment efficiencies it is expected to promote. Since the Tier 2 program is already adopted, the incremental costs that will accrue to capture this N_2O reduction benefit are already accounted for under the Tier 2 program and thus no additional cost will accrue from a GHG perspective.

However, as is also indicated, the 2009 N_2O emission rate is approaching the lower emissions limit (estimated in this study as 0.015 g/mi) imposed by the necessity of conventional three-way catalysts to pass through the warmup temperature band during which the bulk of N_2O formation occurs. Faster excursions to catalyst temperatures above about 400ºC could allow even this lower limit to be “broken,” but there is no available data with which to access the likelihood of significant breakthroughs in this area. It is also important to recognize that the EPA estimates that N_2O emissions for non-catalyst vehicles are in the range of 0.017-0.019 g/mi. [13] This is actually a bit higher than the lower limit emission rate estimated in this study and so is not necessarily a precise comparative datapoint, but the clear implication is that emission rates for catalyst equipped vehicles are approaching those for non-catalyst vehicles.

Nevertheless, it is possible to promote modest additional N_2O reductions through further advances in aftertreatment efficiency. For example, adding advanced technology required to certify vehicles to the Tier 2, Bin 2 level will reduce emissions by a additional 6 percent, but that translates into an absolute CO_2 equivalent reduction of less than 0.3 g/mi. As was the case for methane, since additional emission reduction potential is occurring “at the margin” due to already low emission rates, the cost effectiveness of additional reductions is relatively high. ARB estimates for the incremental retail cost of a SULEV vehicle relative to a ULEV II vehicle provide insight into the cost effectiveness of controlling N_2O to the Tier 2, Bin 2 level. These costs are estimated at about $80 per vehicle. [10] As indicated in Table E-10, this implies a cost effectiveness of about $1,600 per ton of equivalent CO_2 reduction, *assuming all associated costs are attributed to N_2O reduction*. Of course, as described in Section E.2, reductions of methane also accrue, as do reductions in NO_x and NMOG, which could be used to offset a portion of the imposed cost. As both the N_2O and methane reductions accrue in proportion to NO_x and NMOG reductions, it seems most logical to consider these reductions as integral components of Tier 2 and LEV II program reviews, as opposed to independent GHG considerations. This would maintain a consistent approach to continued program development, while properly reflecting both the criteria and GHG emission benefits of such programs.

Table E-10: Cost and Cost Effectiveness of N_2O Reductions

Reduction Strategy	N_2O Change (g/mi)	CO_2 Equivalent Change (g/mi)	Marginal Cost	Cost Effectiveness ($/ton CO_2)
Tier 2,Bin 5 to Tier 2, Bin 2	0.001	0.305	$ 80	$ 1,585
Added Reduction due to CH_4		0.164		
Total GHG Reduction	0.001	0.469	$ 80	$ 1,031

Notes: (1) Cost effectiveness is based on a lifetime mileage estimate of 150,000 miles.

As was the case with the methane analysis presented in Section E.2, it is important to note that the N_2O relationships presented in this study are derived from data for stoichiometric control technology. Existing research indicates that the N_2O formation rate over typical three-way catalysts is quite sensitive to perturbations in air-fuel ratio. At both very rich and very lean conditions, N_2O formation is low due to high active site adsorption rates for non-NO species (CO under rich conditions and oxygen under lean conditions). However, at slightly rich and slightly lean conditions, significant NO adsorption occurs while additional free sites for subsequent N_2O dissociation are limited. [17] Thus, for stoichiometric technology, N_2O is minimized as air-fuel ratio control is optimized. Since future emission standards will result in the introduction of further advances in mixture control as well as continuing improvements in catalyst light off performance, the expectation of continuing N_2O emission reductions for stoichiometric technology, as suggested by the Table E-9 emission rates, is reasonable.

Current diesel engines emit relatively low levels of N_2O due to the absence of catalytic reduction technology. However, the introduction of lean burn aftertreatment technology targeting NO_x control, whether for advanced gasoline or diesel engines, could alter current lean burn N_2O emission rates. [18,19] Lean burn aftertreatment technology such as NO_x adsorbers or selective catalytic reduction (SCR) systems must function under mixture regimes well removed from stoichiometry. Under such conditions and depending on the effectiveness of associated control strategies, N_2O formation could be significant. Current research indicates that N_2O concerns may be more pronounced with SCR systems, but due to the ongoing nature of lean burn aftertreatment system development, it is not possible to assign a reliable N_2O emission rate to any lean burn systems at this time. Given the awareness of aftertreatment developers to N_2O emission concerns, it seem reasonable, however, to assume that design goals will be for emission rates equal to or less than those for current stoichiometric systems. Therefore, for purposes of this study, N_2O emission rates for lean burn technologies are assumed to be the same as those for 2009 (i.e. Tier 2, Bin 5) stoichiometric technology. Clearly, the validity of such an assumption should be monitored as such systems enter the marketplace.

N_2O decomposition catalysts have been patented and are in the initial stages of investigation in the industrial sector. However, these systems are essentially untested in the automotive sector and are likely to face significant challenges such as mechanical and thermal durability, as well as potential sensitivity to exhaust contaminants such as sulfur. [20] Given the ability of the aftertreatment industry to produce the highly effective catalyst systems available in the automotive sector today, there is little doubt that with sufficient leadtime, effective N_2O decomposition catalysts could be introduced. However, given continuing N_2O reductions, the cost effectiveness of additional N_2O decomposition solutions is uncertain. Due to the lack of a prototype system on which to base a costing analysis, no specific cost estimates are developed for this study, but such systems could be considered if alternative lean burn solutions are not found.

Finally, existing research has demonstrated the sensitivity of N_2O formation to fuel sulfur content. [3,4,13] Test data show N_2O emission rate increases of up to 300 percent when fuel sulfur is increased from 20 to 300 ppm. However, this is not considered to be a significant issue in this study as existing federal and California rules require the sulfur content of both gasoline and diesel fuel to be less than 30 ppm on average in the timeframe considered. Thus, all N_2O emission rates estimated in this study assume low sulfur fuel availability. Current emission rates for in-use vehicles may be higher than indicated, but those rates should decline as low sulfur fuels assume a dominating market share over the next few years. Moreover, in any established regulatory structure, emission rates would almost certainly be measured over existing certification cycles for which low sulfur fuels are commonly used.

E.4. Summary

As described in Sections E.2 and E.3 above, emission rates for methane and nitrous oxide have been estimated using an emissions testing dataset for in-use vehicles provided by the ARB. Table E-11 presents a summary of the estimated emission rates. In general, current emissions of both methane and N_2O appear to be quite low relative to emissions of CO_2, estimated at about 0.2 and 6 grams CO_2 equivalent per mile of travel. Moreover, as shown in Figures Q-7 and Q-8, emission rates of both compounds have declined substantially over the last two decades.

A combined CO_2 equivalent emission rate of about 6 g/mi compares to typical tailpipe CO_2 emission rates for current light duty vehicles that range from about 250 g/mi for small cars to 500 g/mi or more for large trucks. Thus, the combined GHG impact of methane and N_2O represents from 1-2 percent of the total CO_2 equivalent emissions from light duty vehicles (ignoring the GHG impacts of emitted water vapor). As presented elsewhere in this study, advanced technology vehicles could achieve reduced CO_2 emission rates in the 2009 to 2015 timeframe of between 150 and 250 g/mi. In this same timeframe, the combined impact of methane and N_2O emissions is estimated to decline to about 5 g/mi, so the combined GHG impact of these species could increase to between 2 and 3 percent of the total GHG impact of light duty vehicles *if* low CO_2 emission technologies are introduced in significant volumes.

Reductions in methane and N_2O emissions beyond those expected to occur by 2009–2015 are possible. However, because the total possible reduction is capped at 5 g/mi CO_2 equivalent, these reductions tend to be relatively expensive from a cost effectiveness standpoint, ranging upwards from about $1,000 per ton of CO_2, as detailed in Sections E.2 and E.3 above. These estimates should be considered in the context of a current absence of regulatory controls on either methane or nitrous oxide. In this absence, research into potential reduction technologies and costs, as well as emission rates is somewhat limited. So it is possible that future developments will improve the cost effectiveness of additional reductions. However, barring significant error in the estimated emission rates, the absolute level of reductions possible at any cost is quite limited.

Table E-11: Estimated Methane and N_2O Emission Rates

Basic Technology Configuration	Methane		Nitrous Oxide	
	2002	2009-2015	2002	2009-2015
Grams per Mile - Expressed as Direct Methane or Nitrous Oxide				
Stoichiometric	0.010	0.008	0.021	0.016
Lean Burn	0.005	0.005	0.016	0.016
Grams per Mile - Expressed as CO_2 Equivalent				
Stoichiometric	0.23	0.18	6.1	4.9
Lean Burn	0.12	0.12	4.9	4.9

Figure E-7: Methane and N_2O Emission Rates by Certification Class

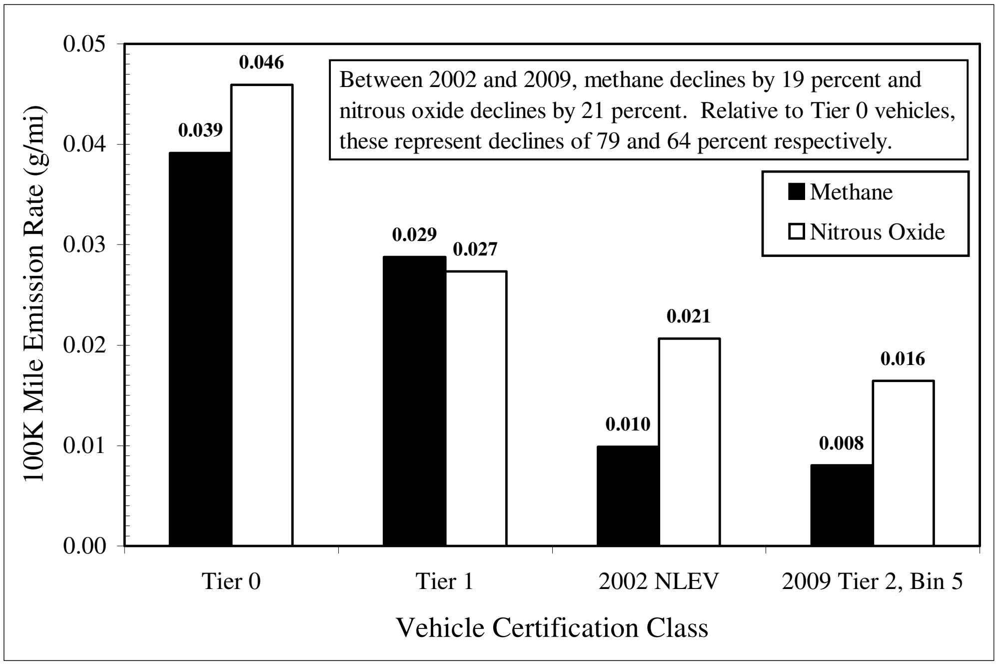
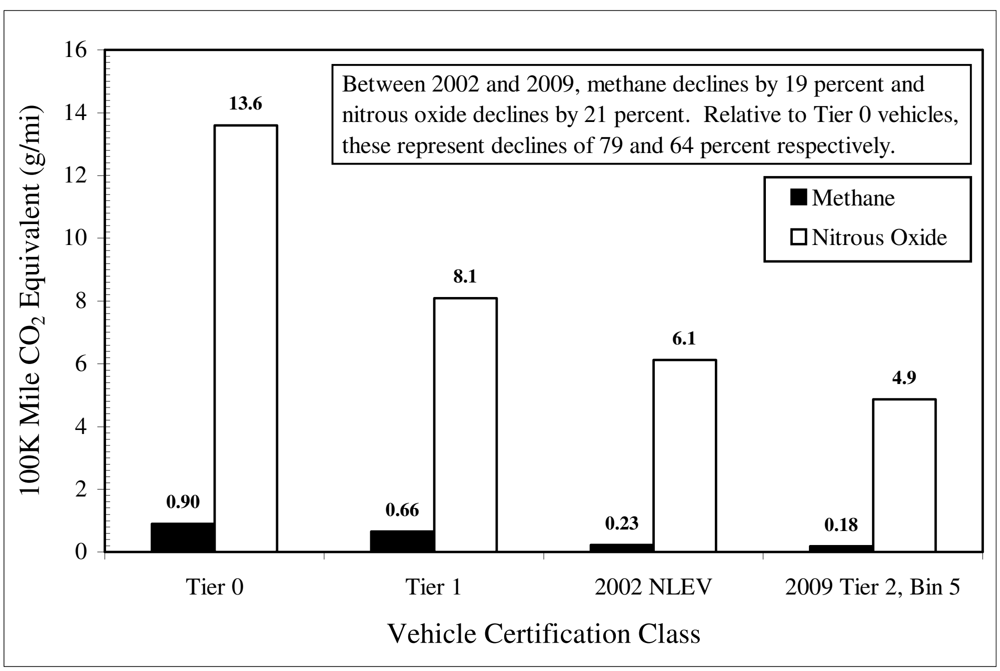


Figure E-8: CO_2 Equivalent Methane and N_2O Emission Rates by Vehicle Certification Class



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