State of California
AIR RESOURCES BOARD

Draft Technology and Cost Assessment for Proposed Regulations to Reduce Vehicle Climate Change Emissions Pursuant to Assembly Bill 1493

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LIST OF ACRONYMS AND ABBREVIATIONS

A4:	4-speed automatic transmission
A5:	5-speed automatic transmission
A6:	6-speed automatic transmission
AB 1493:	Assembly Bill 1493
AdvHEV:	Advanced hybrid
ARB:	California Air Resources Board
AMT:	Automated Manual Transmission
CCP:	Coupled cam phasing
CH_4:	Methane
CNG:	Compressed natural gas
CO_2:	Carbon dioxide
CVVL:	Continuous variable valve lift
CVT:	Continuously variable transmission
DCP:	Dual cam phasing
DeAct:	Cylinder deactivation
dHCCI	Diesel homogeneous charge compression ignition
DMV:	California Department of Motor Vehicles
DOHC:	Dual overhead cam
DVVL:	Discrete variable valve lift
DVVLd:	Discrete variable valve lift, includes dual cam phasing
DVVLi:	Discrete variable valve lift, includes intake valve cam phasing
eACC:	Improved electric accessories
EAT:	Electronically assisted turbocharging
EGR:	Exhaust gas recirculation
ehCVA:	Electrohydraulic camless valve actuation
emCVA:	Electromagnetic camless valve actuation
EHPS:	Electrohydraulic power steering
EPS:	Electric power steering
EMFAC:	Emission Factors model used by ARB (EMFAC2002 v.2.2 April 23, 2003)
EWP:	Electric water pump
FDC:	Fixed displacement compressor
FWD:	Front-wheel drive
GDI-S:	Stoichiometric gasoline direct injection
GDI-L:	Lean-burn gasoline direct injection
gHCCI	Gasoline homogeneous charge compression ignition
GVWR:	Gross vehicle weight rating
GWP:	Global warming potential
HC:	Hydrocarbons
HEV:	Hybrid-electric vehicle
HFC:	Hydrofluorocarbon
hp:	Horsepower
HSDI:	High-speed (diesel) direct injection
ICP:	Intake cam phaser

ImpAlt.	Improved efficiency alternator
ISG:	Integrated starter-generator system
ISG-SS:	Integrated starter-generator system with start-stop operation
L4:	In-line four-cylinder
MAC:	Mobile Air Conditioning
ModHEV:	Moderate hybrid
NMOG:	Non-methane organic gas
N_2O:	Nitrous oxide
NO_x:	Oxides of nitrogen
R-134a:	Refrigerant 134a, tetrafluoroethane ($C_2H_2F_4$)
R-152a:	Refrigerant 152a, difluoroethane ($C_2H_4F_2$)
RPE:	Retail price equivalent
TRR:	Tire rolling resistance
Turbo:	Turbocharging
V6:	Vee-formation six-cylinder
V8:	Vee-formation eight-cylinder
VDC:	Variable displacement compressor
4WD:	Four-wheel-drive
42V ISG:	42-volt integrated starter-generator system

I. INTRODUCTION

A. ASSEMBLY BILL 1493

In July of 2002, Assembly Bill 1493 (AB 1493) was enacted by the State of California. The Bill recognizes the serious impacts of climate change to the State in areas as diverse and wide-reaching as public health, water supply, agricultural productivity, environmental degradation, and catastrophic natural disasters. To mitigate these consequences, the law directs the State to regulate emissions that contribute to climate change from the largest and fastest-growing major source of climate change emissions in California – light-duty passenger vehicles.

In developing the climate change regulations for the State of California, the California Air Resources Board (ARB) staff's technical evaluation includes characterization of statewide greenhouse gases to develop an inventory database, researching the climate change implications on public health and the environment, researching technologies to reduce climate change emissions and their attendant costs, developing credit mechanisms for early or alternative compliance, and creating the climate change regulatory standard. AB 1493 focuses on technology improvements for reductions in climate change emissions, and prohibits requiring vehicle weight reduction, certain vehicle use restrictions, bans on sales of particular types of vehicles, or increases in certain vehicle use and fuel fees as mandatory means for achieving reductions in climate change emissions. A key part of the staff's technical work, and the focus of this report, is an assessment of technologies and fuels that can contribute to a reduction of climate change emissions in passenger vehicles from the 2009 model-year and beyond. The relevant portions of AB 1493 that guide this technology and economic assessment read -

> 43018.5. (a) No later than January 1, 2005, the state board shall develop and adopt regulations that achieve the maximum feasible and cost-effective reduction of greenhouse gas emissions from motor vehicles…. [where] (i) For the purposes of this section, the following terms have the following meanings: (1) ''Greenhouse gases'' means those gases listed in subdivision (g) of Section 42801.1. (2) ''Maximum feasible and cost-effective reduction of greenhouse gas emissions'' means the greenhouse gas emission reductions that the state board determines meet both of the following criteria: (A) Capable of being successfully accomplished within the time provided by this section, taking into account environmental, economic, social, and technological factors. (B) Economical to an owner or operator of a vehicle, taking into account the full life-cycle costs of a vehicle. (Authority cited: Section 43018.5, Health and Safety Code (AB 1493 Pavley))

Since passage of AB 1493, ARB has hosted several meetings to provide an update on the process of formulating climate change emission standards and to solicit feedback and public comment from relevant stakeholders, interested parties, and technology developers. ARB hosted the International Technology Symposium in March of 2003 in an effort to bring together international experts on climate change emission reduction technologies. Leading researchers from the auto industry, vehicle component suppliers, academia, and vehicle simulation firms were invited to speak, covering numerous technologies and their potential to reduce climate change emissions of vehicles in the 2009-2015 timeframe. Staff conducted a workshop on September 18, 2003 to discuss the form of the standard that ARB would ultimately adopt, to discuss a planned economic analysis of the regulation, and to cover emission inventory issues. Additional feedback on developing a climate change regulation came from an update to the Board on November 20, 2003. ARB staff presented its early findings on the individual technologies that are likely to be available in the 2009 timeframe and the potential for climate change emission reductions from these technologies.

Building on the work presented at the earlier public meetings, this report contains a more comprehensive assessment of the technologies considered by the ARB staff in formulating targets for the "maximum feasible and cost-effective reduction of greenhouse gases." The vehicle technology results presented in this report are derived primarily from a comprehensive vehicle simulation modeling effort and a thorough cost analysis performed for the Northeast States Center for a Clean Air Future (NESCCAF). The participants in the study include AVL List Gmbh (AVL), Martec, and Meszler Engineering Services. ARB staff has been monitoring progress of this independent study and has been afforded various opportunities to provide comments on the analysis. ARB staff believes the NESCCAF study is the most advanced and accurate evaluation of vehicle technologies that reduce greenhouse emissions yet performed. ARB staff also met with representatives from EPA, the Society of Automotive Engineers, the Mobile Air Conditioning Society, and the National Renewable Energy Laboratory to develop its approach for reducing the effects of air conditioning refrigerant emissions and excess CO_2 emissions from air conditioning use on climate change.

Beyond this assessment, ARB staff is taking into consideration many other aspects in developing its recommendations for the climate change emission standard. ARB staff will be investigating the potential effects of various forms of the standard and the potential impacts of the standard on driving patterns and vehicle fleet turnover. The staff is also currently evaluating various alternative compliance strategies, such as early compliance strategies and emissions trading mechanisms. These topics are not discussed here, but will be examined in the full ARB Staff Report, scheduled for release in summer 2004.

B. RESEARCH METHOD OVERVIEW

A key part of the ARB staff's technical work is to assess technologies that will be available to reduce greenhouse gases for model year 2009 and later light-duty passenger vehicles. As directed by AB 1493, the technologies assessed need to "achieve the maximum feasible and cost-effective reduction of greenhouse gas emissions from motor vehicles." This section provides a brief overview of the methodology used in the NESCCAF study that serves as the basis of the ARB staff assessment of the potential greenhouse gas reductions and the cost-effectiveness of various available and emerging vehicle technologies.

In Section II, the "Technology Assessment" section, we review NESCCAF's 2002 baseline vehicle attributes, their contribution to atmospheric climate change emissions, and evaluate technologies that have the potential to decrease these emissions. The technologies being explored are currently available on vehicles in various forms or have been demonstrated by auto companies and/or vehicle component suppliers in at least prototype form. Brief generalized descriptions of the technologies and their level of current and potential commercial deployment are provided. Results for climate change emission reductions from more detailed analyses, with specific engine and drivetrain technologies applied to specific vehicles, are presented and summarized. Mobile air-conditioning systems are investigated to determine potential climate change emission reductions from improved efficiency air-conditioning compressors, reduced refrigerant leakage systems, and the use of alternative refrigerants. An assessment of technology options to reduce climate change emissions with the use of alternative fuel vehicles is provided, including analysis of both exhaust and fuel-cycle-related (i.e. "upstream") emissions. Lastly, potential climate change reductions from improved exhaust catalyst technologies are considered.

Many different data sources were used for this analysis. U.S. Environmental Protection Agency data (EPA, 2003) was used to estimate baseline vehicle characteristics, and vehicle systems modeling simulations were used to analyze the potential benefits of various technologies. As indicated before, staff has relied extensively on the NESCCAF 2004 study "Reducing Greenhouse Gas Emissions from Light-Duty Motor Vehicles" for our analysis. It was tailored specifically for the task of formulating a cost-effective vehicular greenhouse gas regulation, and offers the most definitive, contemporary, and relevant research results to date.

The NESCCAF assessment of the costs and benefits of potential climate change reduction technologies relies on vehicle computer modeling simulations in order to reduce the potential error involved with overcounting the potential benefits of clusters of technologies used simultaneously on vehicles. This study also projected 2009 baseline vehicle performance using current trend lines and results of interviews with manufacturers and suppliers concerning production plans relative to performance and weight (the latter being constrained by pending implementation of a Corporate Average Fuel Economy (CAFÉ) increase for light-duty trucks), and the subsequent modeling maintained those outcomes rather than try to change them. The vehicle simulation data used in this assessment rely on a validated model used by the auto industry that includes systems level analyses of the subsystems of the vehicle, including the various types of fuel intake systems, engines, drivetrain configurations, electrical systems, and overall vehicle drag and resistance parameters.

Section III, “Cost Effectiveness of Technologies,” examines the cost effectiveness of the climate change reduction technologies of Section II. The analysis includes a collection of technology cost data, vehicle use data, and general data on economic variables to ultimately determine the cost per ton of lifetime CO_2 equivalent emissions reductions. Our cost estimates associated with the technologies of the previous section again rely to a large extent on the portion of the NESCCAF study conducted by Martec, which specifically analyzes the costs associated with the vehicle technology packages that were examined in the vehicle simulation modeling. Determination of the costs of these technologies involved a detailed investigation of all of the components involved in implementing them in baseline vehicles, with inclusion of the effects of the new technologies on other vehicle systems. The level of detail in the cost analysis again raises the bar relative to any other cost study that we have seen to date. However, there are some aspects of the cost analysis that ARB staff believes need to be modified to meet our long-term cost projection guidelines. Specifically, ARB staff applied additional cost reduction factors for some emerging technologies that account for additional innovation and higher volume learning than was assumed by Martec. In some cases, cost estimates from various other sources were also included in our assessment. California-specific vehicle use data, such as average annual vehicle use and vehicle lifetime, were obtained from the California Department of Motor Vehicles and the ARB’s EMFAC emission model.

Section IV, “Lifetime Cost of Technologies to Vehicle Owner-Operator,” includes a net present value analysis of climate change emission reduction technologies. This assessment is under the direction of AB 1493 to demonstrate climate change reduction technologies that are “Economical to an owner or operator of a vehicle, taking into account the full life-cycle costs of a vehicle.” Here we apply the initial incremental retail price of the technologies, average vehicle use data, and the resulting lifetime cost benefits to the consumer from the technologies to determine whether technology packages are economical over the life of the vehicle.

II. TECHNOLOGY ASSESSMENT

NESCCAF established baseline vehicle characteristics and assessed technologies with potential to reduce greenhouse gas emissions for carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4), and hydrofluorocarbons (HFCs). This was done for five current representative vehicles. These five base vehicles were established in order to compare the differences of various greenhouse gas reduction technologies on various vehicle platforms (e.g. cars, minivans, trucks) with differing characteristics (e.g., maximum power, acceleration).

U.S. Environmental Protection Agency data (from EPA, 2003) was used to establish five representative current vehicles using data from 2002 model year light-duty vehicles. Representative vehicles were chosen to correspond to each of five passenger vehicle classes – small cars, large cars, minivans, small trucks, and light trucks. Separating the fleet into these five subdivisions was done to group vehicles that have similar attributes (e.g. weight, size), have comparable performance (e.g., acceleration), have similar technologies (e.g., transmission types, valvetrain designs), and that are functionally similar. This approach makes the modeling exercise affordable by limiting the number of modeling runs. The approach also acknowledges that some greenhouse gas-reducing technologies may be more applicable to different vehicle classes than others, and each vehicle modeling platform starts from a vehicle that is commercially viable with compatible subsystems.

Table II-1 shows each of the five representative vehicles that was chosen to represent its vehicle class in terms of the following attributes: engine type, number of cylinders, transmission type, maximum power, engine displacement, curb weight, number of transmission speeds, driveline type, and cam type. The table also includes average vehicle class performance characteristics from the EPA (2003) data, including power and acceleration characteristics. Instead of making idealized composite vehicles that had the average or most common sales-weighted vehicle attributes, five actual 2002 model year vehicles were chosen based on closeness of fit to their class average attributes, average performance parameters, and dominant technologies. By choosing existing vehicles, not all characteristics are the exact average of their class. Instead, all the characteristics closely match the class averages, and the vehicles have the advantage of being based on actual existing vehicle platforms.

Table II-1. Representative 2002 Vehicles (NESCCAF, 2004)

		Vehicle class				
		Small car	Large car	Minivan	Small truck	Large truck
EPA-defined vehicle types included[1]		Sub-compact and compact sedans	Mid-size and large sedans	Minivans	Small sport utility vehicles and small pick-ups	Standard pick-ups and large sport utility vehicles
Class average vehicle attributes	Curb weight (lbs)	2762	3380	3980	3714	4826
	GVWR (lbs)				4867	7167
	Engine displacement (liters)	2.27	3.18	3.42	3.41	5.01
	Engine Type	L4	V6	V6	V6	V8
	Charge Type	NA	NA	NA	NA	NA
	Cam Type	DOHC	DOHC	OHV	DOHC	OHV
	Driveline	FWD	FWD	FWD	4WD	4WD
	Transmission Type	Automatic	Automatic	Automatic	Automatic	Automatic
	Number of Transmission Speeds	4	4	4	4	4
	Rated power (hp)	148	194	199	195	257
Performance characteristics	Peak Torque (lb-ft)	152	208	222	218	311
	Power/weight ratio (HP/lb)	0.0530	0.0569	0.0498	0.0524	0.0537
	Torque/weight ratio (lb-ft/lb)	0.0545	0.0610	0.0558	0.0586	0.0649
Representative vehicles for vehicle class		Chevrolet Cavalier 2.2 L I-4	Ford Taurus 3.0 L V-6	Daimler Chrysler Town & Country 3.3 L V-6	Toyota Tacoma 3.4 L V-6	GMC Sierra 5.3 L V-8

Baseline exhaust CO_2 emissions for each of five vehicle classes were based on a combined EPA driving cycle. The EPA combined cycle includes a driving schedule of specific speeds over time to simulate city driving, called the Federal Test Procedure (FTP, also known as the Urban Dynamometer Driving Schedule (UDDS)), and another cycle to simulate highway driving (HWY). Because the resulting emissions from the FTP and HWY cycles are used to determine California vehicle emission certification compliance, using a weighted combination of the CO_2 emissions results from both cycles was deemed appropriate for this assessment.

The greenhouse gas emissions of interest in this report impact the atmospheric radiation budget differently due to their distinct chemical and physical properties. For the purpose of this report, they are expressed in terms of their CO_2 equivalent global warming potential (GWP). Table II-2 lists the GWP value for these gases. The emission rate of 0.005 grams of CH_4 per mile for 2009 baseline vehicles is derived using EMFAC. The emission rate of 0.006 grams of N_2O per mile driven was derived from the ratio of N_2O to oxides of nitrogen derived from emission test data generated at ARB's vehicle test facility.

Table II-2: Global Warming Potential

Greenhouse Gas Compound	Global Warming Potential
Carbon Dioxide	1
Methane	23
Nitrous Oxide	296
HFC 134a	1300
HFC152a	120

Source: IPCC, Third Assessment Report, 2003

Mobile air conditioning has an environmental impact because of both "direct" refrigerant releases and "indirect" exhaust CO_2 emissions. Direct emissions include refrigerant releases from vehicles through air conditioning system leakage (a slow process, sometimes called "regular emissions"), during accidents or other events that suddenly breach containment of the system refrigerant (sometimes called "irregular emissions"), during service events, and when vehicles are dismantled without recovery of the refrigerant. The dominant refrigerant used in vehicle air conditioning systems is 1,1,1,2-tetrafluoroethane, which is a hydrofluorocarbon commonly referred to as HFC-134a. The NESCCAF study also included modeling runs to estimate the total amount of "indirect" CO_2 exhaust emissions that is associated with the use of the air conditioning system. Both the "indirect" CO_2 emissions and the CO_2-equivalent "direct" HFC emissions are summarized in Table II-11 and Table II-12.

In the following subsections (A.) through (E.), technologies with potential to make net reductions in total baseline vehicle greenhouse gas emission levels are investigated. The technologies involved are briefly described and the potential emission reduction benefits are quantified. The assessment of technology options to reduce these emissions is split into the five generalized technology areas:

A. Engine, Drivetrain, and Other Vehicle Modifications – valvetrain, transmission, vehicle accessory, hybrid-electric, and overall vehicle modifications designed to reduce engine exhaust CO_2 emissions from conventional vehicles
B. Mobile Air-Conditioning (MAC) System– air conditioning unit modifications to reduce vehicle CO_2 emissions and refrigerant modifications to reduce emissions of HFC refrigerants, such as HFC-134a
C. Alternative Fuel Vehicles – the use of vehicles that use fuels other than gasoline and diesel to reduce the sum of exhaust emissions and "upstream" fuel-delivery emissions of climate change gases
D. Exhaust Catalyst Improvement – exhaust aftertreatment alternatives to reduce tailpipe emissions of CH_4 and N_2O

A. ENGINE, DRIVETRAIN, AND OTHER VEHICLE MODIFICATIONS

This section includes research into the potential to reduce tailpipe carbon dioxide emissions with the introduction of various available or emerging valvetrain, engine, transmission, vehicle accessory and body improvement technologies on conventional gasoline and diesel vehicles by model year 2009. The assessment relies primarily on the NESCCAF (2004) analysis, which establishes baseline 2009 vehicle characteristics and evaluates the potential CO_2 reductions from individual technologies and packages of multiple technologies.

1. Carbon Dioxide Reduction Technologies

This subsection provides brief, generalized descriptions of the carbon dioxide reduction technologies and their levels of commercial deployment. The technologies being explored for carbon dioxide emission reductions are currently available on vehicles in various forms or have been demonstrated by auto companies or vehicle component suppliers in prototype form, so as to conform to the 2009 – 2015 timeframe of the assessment. Although general estimates for potential CO_2 reductions can be found in the technical literature, they are not reported here because improved and more detailed estimates are obtained from the vehicle simulation modeling results below for one or more of these technologies on specific vehicles. These technologies are contained either in or around the engine itself, pertain to the transfer of motive force between the engine and the wheels through the drivetrain, or involve overall vehicle changes. Those technologies contained in the engine include modifications to the functioning of the intake and exhaust valves, the charge type, or the injection and preparation of the fuel or fuel-air mix into the cylinders. Drivetrain technologies that could reduce greenhouse gases include modifications to the transmission and various degrees of hybridization. This section offers a brief description of these technology options. Abbreviations for each of the technologies within each description in this section are used to refer to the technologies in shorthand in later sections of this report.

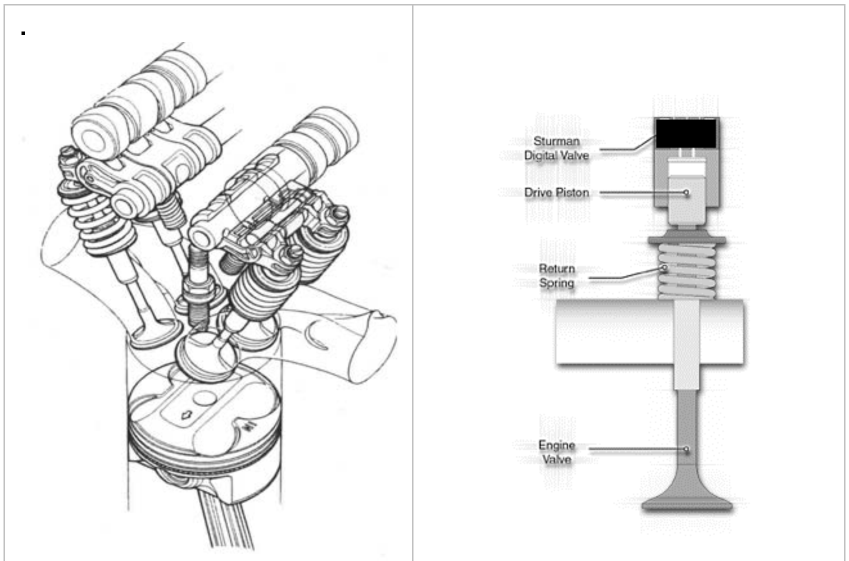
Factors that affect CO_2 emissions from an engine include friction of internal components and the presence of a throttle that restricts airflow into the engine, thereby resulting in pumping losses. The remainder of the driveline also contributes to higher CO_2 emissions due to frictional and hydraulic losses in the transmission and differential or transaxle. Further, CO_2 emissions are increased due to the work performed by the engine to run accessories needed to maintain the electrical system, operate the power steering and air conditioning compressor, or from operation of other devices. CO_2 emissions are further increased when the engine has to work to overcome inertial forces due to vehicle weight during acceleration or hill climbing, to overcome wind resistance, or to overcome tire rolling resistance. Shutting off the engine when possible during idling reduces CO_2 emissions and using a regenerative braking system for capturing otherwise lost energy to assist in relaunching a vehicle from a stop also minimizes CO_2 emissions production.

Engine Valvetrain Modification
Valve timing and lift have historically been fixed for most manufacturers regardless of vehicle load demand. Variable valve timing, also known as “cam phasing,” and variable valve lift can improve engine carbon dioxide emissions by more optimally managing precisely when the valves open and close and exactly how much they open and close. Cam phasing can be varied either by linking the intake and exhaust cams together and rotating them with one phaser (CCP) or independently using dual cam phasers (DCP)

for varying engine operation conditions. Valve lift technologies can be introduced to make continuous variations in lift (CVVL) or make discrete valve height lift increments (DVVL). These technologies can also be introduced either singly or in combination, providing reduced engine pumping losses, improved power output that permits engine downsizing, and substantial CO_2 reductions.

Increased control of intake and exhaust valves also provides for selective cylinder deactivation (DeAct) by closing both sets of valves. The selective deactivation of cylinders allows each of the other still-active cylinders to operate in more optimal regions of higher loads (higher torque and/or engine speeds) and reduces pumping losses. The technology has been found to be better suited for vehicles with relatively high engine displacement to weight ratios and engines with at least six cylinders.

More advanced and offering even greater improvements are camless valve actuation (CVA) systems that replace a belt, chain- or gear-driven camshaft system with variable electrohydraulic or electromagnetic actuation of the valves. Electrohydraulic actuation systems provide greater potential to reduce CO_2 emissions than electromagnetic systems since less power is required for system operation throughout the engine speed range. As shown in Figure II-1, electrohydraulic camless valve systems are relatively simple in their design and operation. Electromagnetic systems continue to have issues with valve closing force and attendant noise, but progress is being made according to some. Also, electrohydraulic systems can incorporate variable valve lift more readily. However, there are proponents for both systems who strongly believe they will be in volume production in the 2012 timeframe. Camless valve actuation is the ultimate goal of engine designers to achieve optimum valve position and lift for maximum engine performance and lowest CO_2 emissions over the full range of engine operation. Engines with CVA systems do not need a throttle and can deactivate cylinders at anytime as opportunity exists. Staff is aware of significant development activity taking place in Europe and Japan. Manufacturers that develop this technology such that they are first to market will have a strong competitive advantage. It also represents a more logical next step for manufacturers of overhead valve engines than going to overhead cam designs that might be short-lived should camless valve actuation come to fruition as early as the 2010 timeframe as is now predicted.



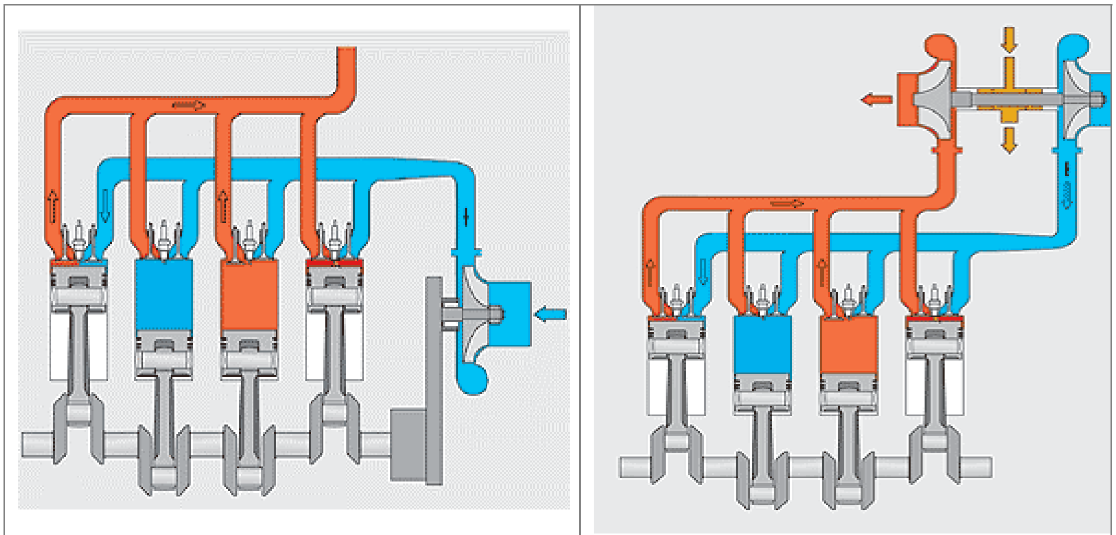
Variable valve timing and lift
(Honda V-tec system)

Electrohydraulic valve actuation
(Sturman DHOS Valve Technology)

Figure II-1: Two Variable Valve Systems

Charge Modification

In conventional gasoline-fueled passenger vehicles, air-fuel mixture (i.e. “charge”) enters the cylinders near ambient pressure. Increasing, or “boosting”, the pressure of the air-fuel mix in the cylinder results in a higher specific power output from the engine. Therefore, the use of a supercharging or turbocharging compressor to increase the charge entering the cylinders improves engine power output and offers the opportunity to downsize the engine without compromising vehicle performance, thereby allowing operation of the engine in more optimal, low-CO_2 regions. A supercharger (Super) offers this advantage by using mechanical power directly off the main engine. A turbocharger system (Turbo) utilizes the otherwise lost thermal energy of the exhaust to operate a turbine, which then drives a compressor. Both of these systems are shown schematically in Figure II-2. Superchargers were not modeled in the NESCCAF study since they do not offer the level of CO_2 benefits achieved from turbochargers and are generally more costly. Current state of the art turbochargers incorporate a variable geometry feature that provides quicker boost at all speeds to maintain performance from downsized engines, especially at lower speeds where “turbo lag” can otherwise result in sluggish performance.



Mechanical power supercharging
(BorgWarner Turbo Systems)

Exhaust gas turbocharging
(BorgWarner Turbo Systems)

Figure II-2: Schematics for Supercharged and Turbocharged Engines

Variable Compression Ratio

Engine compression ratio is a key determining factor for optimal engine operation and lower CO_2 emissions. Current gasoline engines generally use a compression ratio of about ten-to-one and are limited from using higher ratios by pre-ignition or “knocking” at high loads. Because knocking generally increases with engine load, overall CO_2 emissions can be improved with the use of higher compression ratios at lower loads and lower compression ratios under higher loads with the use of variable compression ratio (VCR) technology that can vary cylinder geometry. This technology, however, is relatively expensive to implement given its current state of development and better CO_2 reductions can be obtained from other approaches at less cost. Therefore, the NESCCAF study did not include modeling of this technology.

Gasoline Direct Injection

Carbon dioxide reductions can be achieved through modifications of the fuel injection system of gasoline vehicles to directly inject the fuel into the cylinder where the air is already compressed (conventional engines inject fuel into the intake manifold ahead of the intake valve, wherein fuel evaporates and is inducted into the cylinder with the incoming air). This can be done under stoichiometric (i.e., using only enough air to burn the fuel) or “lean burn” (i.e., excess air) conditions. Due to thermodynamic improvements, lean burn GDI (GDI-L) systems can offer substantial CO_2 reductions, but with some complications involved in controlling oxides of nitrogen (NO_x) emissions. Advances in lean burn aftertreatment devices similar to those being developed for diesel engines may offer a solution. Stoichiometric GDI (GDI-S) systems offer smaller CO_2 reductions than GDI-L technology, but without NO_x aftertreatment concerns.

Homogeneous Charge Compression Ignition

Through precise control of the temperature and pressure in the combustion chamber, spontaneous and homogeneous ignition of the air fuel mixture can occur. Since combustion occurs simultaneously throughout the combustion chamber without forming a flame front and at lower temperatures than conventional spark ignited engines, engine-out particulate matter (PM) and NO_x emissions are very low. Homogeneous charge compression ignition (HCCI) can offer substantial CO_2 emission reductions and can be applied to engines using a variety of fuels, including gasoline and diesel. While significant effort is being directed to its development, some technical challenges remain before it becomes commercially applicable. At present, HCCI operation is possible only in a portion of the engine operating range. Therefore gasoline engines with this capability are based on a direct injection engine wherein its spark ignition capability is retained for the non-HCCI operating modes that will continue to require a spark to ignite the mixture.

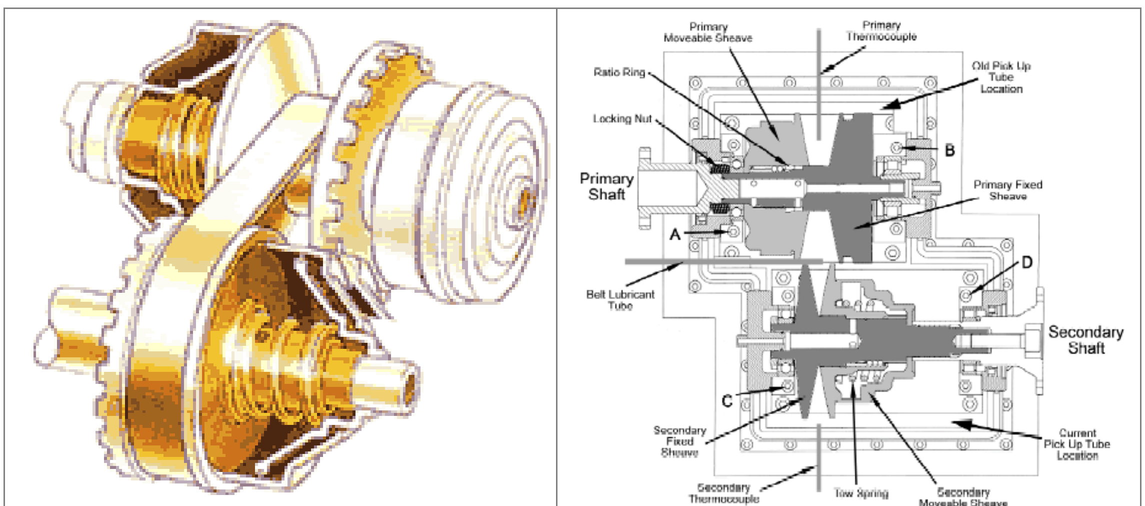
Diesel Fuel
High speed direct injection (HSDI) diesel vehicles have improved with the advancement of several technologies. Diesel compression-ignition engines, with higher compression ratios, turbocharging, and lean air-fuel ratios provide significant CO_2 reductions compared with conventional gasoline engines. Advancements in small diesel engines running at high speeds (over 4000 rpm compared to heavy-duty diesel engines at less than 2000 rpm) in the areas of fuel injection, emissions, noise, and vibration have addressed many of the more objectionable aspects of these vehicles, making them more acceptable to the public. Diesel vehicles are becoming popular in Europe but face a substantial challenge meeting more stringent emission standards in the U.S. Advanced multi-mode diesel engines combine homogeneous charge compression ignition operation at lower engine speeds and loads to minimize particulate, NO_x and CO_2 emissions compared to conventional diesels and revert to conventional diesel engine operation at higher speeds and loads to ensure expected power levels. Maximum use of homogeneous charge combustion operation reduces CO_2 emissions and lessens the burden of aftertreatment of NO_x and PM emissions.

Engine Accessory Improvement
Improvements to various electrical components on vehicles can provide significant improvements in CO_2 emissions. Electrification (eACC) of engine accessory subsystems, such as coolant pumps and other accessories, can reduce the overall losses associated with powering them mechanically. Electrifying the power steering for most cars or utilizing an electro-hydraulic power steering system for larger cars and trucks is also being considered for its contribution to total vehicle CO_2 emissions. Improvements in the vehicle alternator (ImpAlt) that would power these accessories can also provide greater benefits.

42 Volt Systems
Upgrading of vehicle electrical systems to 42 volts (42V), a step many manufacturers are currently contemplating, is an enabling technology for more diverse electrical opportunities. The 42-volt electrical system can accommodate more powerful electrical accessories on-board the vehicle and an integrated starter generator. An integrated starter-generator 42-volt vehicle system (ISG 42v) recoups energy while decelerating through regenerative braking and provides instantaneous engine restart to avoid engine idling; some variants can provide power assist in vehicle acceleration.

Transmissions

Automatic transmissions on today's vehicles generally have 4 gear ratios, or speeds. Increasing the number of gears to 5- or 6-speeds, as has already been done in numerous vehicle models, allows the engine to operate in more optimum operating ranges for lowest CO_2 emissions during the drive cycle. Each increase in number of speeds corresponds approximately to a two percent reduction in CO_2 emissions. More advanced transmissions may offer more substantial improvements. The automated manual transmission (AMT) acts like a conventional automatic transmission in that shifting is performed automatically, but no torque converter used. AMTs operate with either one or two electronically controlled clutch mechanisms. Some of the transmissions are in production in Europe. These transmissions may need some additional refinement to achieve the shift quality of conventional automatic transmissions and to improve driveline vibration. Just as increasing the number of gears from 4 to 5 speeds or more allows the engine to operate closer to its ideal operating point at any given time, the continuously variable transmission (CVT) provides engines a greater ability to operate at precisely the optimal speed for the required load. The CVT effectively acts as a transmission with an infinite number of gears, using either a belt or chain on a system of two pulleys (see Figure II-3). At this time, however, manufacturers seem to be obtaining most of the CO_2 emission reductions of a CVT by using a 6-speed automatic transmission at significantly less cost. Therefore, few of the modeling runs incorporated CVTs.



Honda CVT

Schematic for CVT developed by General Motors and Southwest Research Institute

Figure II-3: Continuously Variable Transmissions

Hybridization

Hybridization, or use of both combustion engines and electric motors for propulsion, is being actively explored by all major auto manufacturers. Hybridization of current and planned vehicles varies widely from "mild" hybrids, which tend to be more similar to conventional gasoline passenger vehicles to fully-integrated "advanced" hybrids that use and store more electric energy on-board. Differentiating the mild system from more advanced hybrids is the increased extent to which electrical power is stored on the vehicle and used during driving. In a fully integrated hybrid (e.g., Toyota Prius), the electric motor approaches the same size as the on-board combustion engine and therefore can be used exclusively to power the vehicle during low-load, low speed conditions. In the moderate “motor-assist” hybrid configuration, such as the Honda Civic Hybrid, the maximum power output of the engine is substantially greater than that of the electric motor. The electric motor then is generally used for times of higher load demands, such as acceleration or hill climbing, providing for engine downsizing and optimization for low load conditions such as cruising. Mild hybrids generally offer only idle off capability. Compared with similar performing conventional vehicles, moderate to aggressive hybrids can achieve improvements of over thirty percent in CO_2 emissions. Along with the commercially available Toyota and Honda hybrid vehicles, every major automaker has introduced plans to mass produce hybrid vehicles in the next few years. EPA is investigating the potential of hydraulic hybrids and has published an interim report on their progress. A brief summary of this technology can be found in Appendix A.

Engine Friction Reduction
Due to the large number of internal parts in today’s engines coupled with numerous accessory drives, improvements in the design of engine components and subsystems can continue to drive friction reductions, resulting in improved engine operation and reduced climate change emissions. Friction reductions in and around the engine can result from such measures as engine component weight reduction, use of different materials, more optimal thermal management, and improved computer-aided understanding of component dynamics under various engine load and vibration conditions. Further friction reductions result from the use of advanced multi-viscosity engine and transmission oils.

Aerodynamic Drag and Rolling Resistance Reduction
Improvements in the overall force required to propel a vehicle reduces engine load thereby leading to a reduction in vehicle exhaust CO_2 emissions. Two ways to reduce the engine load for a given vehicle are to reduce the opposing resistance or frictional forces that act against the motion of the vehicle. Two prominent resistance forces are aerodynamic drag and rolling resistance at the tires. The most obvious areas for potential aerodynamic drag improvements are reducing the frontal area of the vehicle or improving the shape of the body, with skirts, air dams, underbody covers, and other features that have less aerodynamic friction. The rolling resistance force due to friction between the tires and the road can be improved via shoulder design improvements or with design and material modifications to the tire tread pattern, tire belts, or the traction surface.

Aggressive Shift Logic
Shifting schedules, or the engine speed at which automatic transmissions switch from one gear ratio to another, can have a substantial impact on CO_2 emissions. Using a more aggressive shift logic allows more flexible shifting of gears and thus allows for operation of the engine at more optimal low CO_2 emission regions of the engine maps. Generally, aggressive shift logic entails moving transmission upshift points to lower speeds and reducing the amount of downshifting. Driveability and acceleration concerns must be accounted for carefully in these alterations of shifting schedules.

Early Torque Converter Lock-up
Conventional automatic transmissions employ a torque converter between the engine and transmission. This is a fluid coupling with hydraulic torque multiplication capability that helps provide a brisk "launch feel" to vehicles so-equipped. They also dampen engine vibrations in the driveline and allow engines to remain at idle speeds with the transmission engaged in a forward or reverse gear. Unfortunately, the torque multiplication at launch and the other features result in higher CO_2 emissions compared to a manual transmission. In order to reduce slip, virtually all of today's automatic transmissions offer some degree of lock-up capability during some light accelerations and during cruise conditions (this means the torque converter no longer slips needlessly and provides direct or near-direct mechanical transmission of power to the drive wheels much like a manual transmission). The conditions under which lock-up operation occurs can be improved by doing so earlier than at present, especially when the number of transmission speeds increases, thereby reducing CO_2 emissions. As with early shift speeds, however, care must be exercised to ensure smooth, responsive driveability and low noise, vibration, and harshness. AVL was conservative in its modeling of these features to ensure good driveability and minimum vibration.

Weight Reduction
Although ARB staff efforts will not rely on weight reductions in setting its climate change emission standards, manufacturers would still have the option of lowering weight to improve CO_2 emission performance. Lower weight results in lower CO_2 emissions by lowering the forces needed to accelerate the vehicle and climb grades. Lower weight can be achieved by substitution of lighter materials, better packaging, and shifting to a smaller platform. Besides the use of high strength low alloy steels, some manufacturers are relying on more use of aluminum and magnesium alloys and plastics to achieve greater weight savings, although at somewhat higher cost than steel.

2. Summary of Vehicle Simulation Modeling Results

As was alluded to above, a detailed vehicle simulation model was used in the NESCCAF study to predict baseline 2002 CO_2 emissions and to estimate CO_2 emission reductions from applying various combinations of technologies to the baseline vehicles. The year 2002 is held as a base year for the calculations because it is the year that the modeling platforms were built upon and it is most recent year for which extensive and actual knowledge on the vehicle fleet was available. Moreover, emissions are reported using the 2002 model year as a baseline because it is likely to be the year that will later be used in quantifying pre-2009 climate change reduction credits. Because the pending regulation would be applicable for model year 2009 and later vehicles, potential reductions for 2009 vehicles are also provided in the summary and used for assessment of the cost-effectiveness of the new technologies.

The modeling presented here (and in NESCCAF) utilizes the vehicle simulation model developed by AVL Powertrain Engineering, Inc. called CRUISE. The modeling software is designed for the advanced study of various vehicle platforms to provide estimates of vehicle performance, emissions, and fuel usage. The modular systems-based nature of the CRUISE software allows for investigation of sophisticated and detailed analyses of each vehicle component, from the fuel intake system and engine through the drivetrain to the tires. An advantage of systems-modeling such as this is to allow a wide diversity of combinations of technologies to be modeled together and examine how they interact together when simulating a vehicle driving on various driving cycles.

The AVL CRUISE model was first used to create the five 2002 representative vehicle simulation models with representative attributes and to validate these models with the known actual vehicle performance characteristics. In addition to modeling the 2002 representative vehicles, separate 2009 baseline vehicles were characterized through analysis of vehicle trends and market research in order to quantify costs and benefits of vehicle technologies. The NESCCAF study uses EPA data on vehicle trends to characterize vehicle class characteristics and market research by MARTEC to forecast vehicle technology platforms that will dominate the base case, or “business-as-usual,” (i.e. absence of new regulations) 2009 model year vehicles. With the use of historical trends from the EPA (2003b) dataset, the baseline vehicle characteristics of acceleration and weight were examined. The 0-60 miles-per-hour acceleration changes for the five vehicle classes were projected to increase by seven to sixteen percent for the 2009 model year. Averaged vehicle inertia weights were projected to hold constant for all the classes except for small cars due to historical trends and pending implementation of federal CAFÉ regulations.

The NESCCAF study highlights several key technology changes for their “business-as-usual” scenario for the 2009 model year. The MARTEC market research projected the technologies that are likely to enter the vehicle fleet to deliver the power and acceleration requirement for 2009 for each of the five vehicle classes. The primary differences from the 2002 fleet are the widespread introductions of emerging engine valvetrain and transmission technologies. Introducing cam phasing technology to alter the timing of intake and/or exhaust valves during engine operation is forecasted to dominate in each vehicle class, and all classes but the large truck are expected to have some form of variable valve lift technology. Each vehicle class is expected to increase the number of transmission gears from four to either five (for small cars and minivans) or six (large cars, small trucks, and large trucks). All vehicles were then modeled on a combined EPA driving cycle.

The technologies for reducing CO_2 emissions were modeled both individually and in various technology packages by AVL. A summary of the modeling results for individual technologies from the NESCCAF study is shown in Table II-3. In the table, the baseline 2002 CO_2 emission rates, in grams per mile, for each vehicle class are shown, and the results from the other modeling runs are shown as percentage reductions from these baseline values. Modeling of single technologies often was accomplished through partial CRUISE modeling or use of other abbreviated simulation techniques to save cost in the study. This seems reasonable since this step was only intended to provide an estimate of the benefits in order to provide a basis for the technology combinations that were selected for full CRUISE modeling.

This report relies on internal ARB analysis of hybrid electric vehicle benefits and costs. Although the NESCCAF (2004) report did study the effect of moderate and advanced hybrid-electric vehicles, the analysis was less detailed and less comprehensive than their intricate modeling of the other technologies due to cost and time constraints. As a result, the ARB staff opted to do an independent review of HEV CO_2 emission reduction capability and cost, using real-world data from currently available vehicle platforms and field interview from component manufacturers (See Appendix A).

Table II-3. Potential Carbon Dioxide Emissions Reductions from Individual Technologies (from NESCCAF, 2004)

	Vehicle Class				
	Small car	Large car	Minivan	Small truck	Large truck
Baseline 2002 CO_2 emissions (g/mi)	291.4	344.6	395.4	444.7	511.6
Technologies	*Percent reduction from 2002 baseline*				
Near Term Technologies 2009-2012					
Intake Cam Phasing	-2%	-1%	-1%	-1%	-2%
Exhaust Cam Phasing	-2%	-3%	-2%	-2%	-3%
Dual Cam Phasing (DCP)	-3%	-4%	-2%	-3%	-4%
Coupled Cam Phasing (CCP)	-3%	-4%	-2%	-2%	-4%
Discrete Variable Valve Lift (DVVL)	-4%	-4%	-3%	-4%	-4%
Continuous Variable Valve Lift (CVVL)	-5%	-6%	-4%	-5%	-5%
[2]Turbocharging (Turbo)	-6%	-8%	-6%	-6%	
[3]Electrically Assisted Turbocharging (EAT)	-6%	-8%	-6%	-6%	
[2]Cylinder Deactivation (DeAct)	-3%	-6%	-5%	-6%	-4%
[1]Variable Charge Motion (CBR)	-3%	-4%	-2%	-3%	-4%
[5]Variable Compression Ratio	-7%	-7%	-7%	-7%	-7%
[5]Gasoline Direct Injection - Stochiometric (GDI-S)	0%	-1%	1%	1%	0%
[2]4-Speed Automatic Transmission	0%	0%	0%	0%	0%
[2]5-Speed Automatic	-2%	-1%	-1%	-1%	-1%
[2]6-Speed Automatic	-3%	-3%	-3%	-3%	-2%
[6]6-Speed Automated Manual	-8%	-7%	-8%	-8%	-5%
[2]Electric Power Steering (EPS)	-1%				-1%
[3]Electro-Hydraulic Power Steering (E-HPS)	-1%				-1%
[2]Improved Alternator (Higher efficiency)	-1%				0%
[2]Electric Accessories	-3%				-2%
[3]Aggressive Transmission Shift-Logic	-1.5%	-1.5%	-1.5%	-1.5%	-1.5%
[3]Early Torque Converter Lock-up	-0.5%	-0.5%	-0.5%	-0.5%	-0.5%
[2]Variable Displacement AC Compressor	-10%	-9%	-7%	-9%	
[2]Aerodynamic Drag Coefficient (% CO_2 / % Cd)	0.165				0.192
[2]Improved Tire Rolling Resistance (% CO_2 / % TRR)	0.180				0.204
Mid Term 2013-2015					
[1]Electromagnetic Camless Valve Actuation (emCVA)	-11%	-11%	-11%	-11%	-11%
[2]Electrohydraulic Camless Valve Actuation (ehCVA)	-11%	-16%	-11%	-13%	-12%
[5]Gasoline Direct Injection - Lean-Burn Stratified (GDI-L)	-6%	-9%	-4%	-5%	-8%
[5]Gasoline Homogeneous Compression Ignition (gHCCI)	-4%	-6%	-3%	-4%	-5%
[2]Continuously Variable Transmission (CVT)	-4%	-3%	-4%		
[2]Electric Water Pump (EWP)	0%				0%
[2]42-Volt 10 kW ISG (Start Stop)	-7%	-4%	-4%	-4%	-5%
[2]42-Volt 10 kW ISG (Motor Assist)	-10%	-6%	-6%	-6%	-5%
[2]Diesel – HSDI	-20%	-22%	-24%	-27%	-23%
Long Term 2015-					
[6]Moderate Hybrid-Electric Vehicle (HEV)	29%	29%	29%	29%	29%
[6]Advanced Hybrid-Electric Vehicle (HEV)	54%	54%	54%	54%	54%
[2]Diesel – Advanced Multi-Mode	-13%	-15%	-18%	-21%	-17%

[1] Based on Literature Search; [2] Based on Full AVL CRUISE Simulation; [3] Based on Combined Literature/AVL CRUISE Simulation; [4] Estimated Value; [5] Additional Reduction due to Downsizing is not Included; [6] HEV numbers based on internal ARB analysis (not from NESCCAF, 2004), See Appendix A

Given the multitude of technologies available for reducing vehicle CO_2 emissions, there needs to be some engineering guidelines for choosing combinations that would make sense to achieve cost effective CO_2 reductions. Generally it is important to avoid combining technologies that tend to address the same categories of losses or technologies that may not complement each other from a driveability standpoint. For example, it would not be advisable to combine cylinder deactivation capability with a lean burn gasoline direct injection engine design since both technologies address reductions in pumping losses within an engine. Also, when transitioning in and out of the deactivation mode, operating in a lean burn mode at the same time could make the transitions more noticeable to the driver since larger throttle changes would be needed to ensure constant engine torque than if the vehicle were operating in a stoichiometric mode.

Some technologies are attractive to combine because their features enhance each other. For example, combining cylinder deactivation with stoichiometric gasoline direct injection makes sense since the transitions in and out of the deactivation mode tend to introduce fuel control challenges due to the abrupt changes in operating modes that occur. By using a direct injection concept where fuel is introduced directly into the combustion chamber, control of transient fueling is much more precise. This is because fuel preparation and wall wetting issues in the intake passages encountered with conventional engines introduce fueling errors in transient engine operation. The more precise control afforded by direct injection would therefore be an enabler for some engines to meet the lowest emission categories in the Low-Emission Vehicle program when utilizing cylinder deactivation.

Some technologies are attractive because they provide elegant solutions to minimizing CO_2 emissions. One such technology is electrohydraulic camless valve actuation combined with stoichiometric gasoline direct injection. This technology permits operating the engine in modes that generate the lowest CO_2 emissions at all times with minimum complexity. It would allow operation without a throttle to minimize pumping losses, could employ cylinder deactivation whenever it was useful, and would provide the maximum flexibility necessary to achieve maximum performance from a given engine displacement, thereby enabling smaller engine displacements. Again, stoichiometric gasoline direct injection would further complement this technology because it permits higher compression ratios due to the cooling effect of fuel evaporation in the combustion chamber, thereby affording more optimal engine operation from a low CO_2 emission standpoint.

AVL provided a chart summarizing the most appropriate engine technologies to group for achieving the most cost effective CO_2 emission reductions (Figure II-4). The chart is read first across and then down (as illustrated by the arrow) to determine which technologies are compatible. For example, turbocharging is considered compatible with all technologies except GDI lean burn, since both technologies address the same engine pumping losses. Therefore, it is unlikely that a manufacturer would combine these two technologies. This table was used by NESCCAF participants when they constructed their technology combinations.

Feasible Technology Combinations	Cam Phaser - Single (Intake Cam)	Cam Phaser - Single (Exhaust Cam)	Cam Phaser - Dual	Cam Phaser - Coupled	Variable Valve Lift - Discrete	Variable Valve Lift - Continuous	Camless Valve Actuation - Electrohydraulic	Turbocharging	Electrically Assisted Turbocharging (EAT)	Cylinder Deactivation	Variable Charge Motion (CBR)	GDI Stochiometric	GDI Lean Burn Stratified	Gasoline HCCI	Diesel – HSDI	Diesel – Advanced Multi-Mode
Cam Phaser - Single (Intake Cam)																
Cam Phaser - Single (Exhaust Cam)	NO															
Cam Phaser - Dual	NO	NO														
Cam Phaser - Coupled	NO	NO	NO													
Variable Valve Lift - Discrete	YES	YES	YES	YES												
Variable Valve Lift - Continuous	YES	YES	YES	YES	NO											
Camless Valve Actuation - Electrohydraulic	NO	NO	NO	NO	NO	NO										
Turbocharging	YES	YES	YES	YES	YES	YES	YES									
Electrically Assisted Turbocharging (EAT)	YES	YES	YES	YES	YES	YES	YES	NO								
Cylinder Deactivation	YES	YES	YES	YES	YES	NO	YES	NO	NO							
Variable Charge Motion (CBR)	YES	YES	YES	YES	YES	YES	YES	NO	NO	YES						
GDI Stochiometric	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES					
GDI Lean Burn Stratified	YES	YES	YES	YES	NO	NO	NO	NO	NO	NO	NO	NO				
Gasoline HCCI	YES	YES	YES	NO	YES	NO	YES	NO	NO	NO	NO	NO	NO			
Diesel – HSDI	NO	NO	NO	NO	NO	NO	YES	YES	YES	NO	NO	NO	NO	NO		
Diesel – Advanced Multi-Mode	NO	NO	NO	NO	NO	NO	YES	YES	YES	NO	NO	NO	NO	NO	NO	

Figure II-4. Feasible Technology Combinations

Having selected a variety of engine technologies, further choices are available relative to the rest of the driveline for enhancing low CO_2 performance. Transmissions with more gear ranges allow the engine to operate more of the time in a low CO_2 mode, and continuously variable transmissions provide an unlimited number of ratios for achieving improvements. Use of a 6 speed automated manual transmission affords further reductions in CO_2 since it allows elimination of the torque converter utilized in a conventional automatic transmission or continuously variable transmission. CO_2 savings also result from use of integrated starter generators that permit shutoff of the engine when the vehicle is not in motion. Further, more capable integrated starter generators permit capture of braking energy that can be redeployed during relaunch of the vehicle to further minimize production of CO_2.

Engine accessories can also be designed to reduce CO_2 emissions through such technologies as variable displacement air conditioning compressors described later plus such features as electric power steering and improved efficiency alternators.

With these guidelines in mind, participants in the NESCCAF study assembled a wide variety of combined technologies to evaluate through simulation modeling those combinations that would provide the greatest CO_2 reductions. ARB staff provided some suggested technology combinations for full simulation modeling.

Table II-4. 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 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		
Total Potential (Excludes 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
Average RPE per Percent CO_2		\$25	\$29	\$30
Assumed Improvement	Impact	5% CO_2 reduction	5% CO_2 reduction	4% CO_2 reduction
	Cost	\$125 RPE	\$145 RPE	\$120 RPE

Notes: from NESCCAF, 2004

Table II-4 lists the CO_2 improvements that can be achieved through various technologies such as lower rolling resistance tires and aerodynamic drag reduction. These improvements are included in the CO_2 benefits listed Tables II-5 through II-9 below containing the simulation modeling results for various combinations of individual technologies using the 2002 vehicle platforms.

Guidelines contained in Figure II-3 as well as cost, served as the basis for the selections in the following tables. The study participants also wanted to cover the full spectrum of CO_2 reductions that would be possible. We have partitioned the results into three categories for near-, mid-, and long-term *volume* application. Thus, while hybrid vehicles are available now in several models, they were nonetheless grouped with the long-term strategies since high volumes of moderate to aggressive hybrids probably would not occur until the long term. Additional time is needed to sort out level of consumer acceptance, suitability in various applications, long term durability and other issues that include investment resources across industry to accomplish large scale conversion to a significantly different technology than currently exists in the vehicle fleet.

In the following tables, CO_2 emission reductions and package costs are shown relative to both the 2002 and 2009 baselines that were established in the NESCCAF report. When describing the results following each table, the text highlights the CO_2 reductions relative to the 2002 baseline because this is the reference most studies use. For describing the costs, however, staff cites them relative to the 2009 baseline because those would be the actual increment that the consumer would see when purchasing a 2009 and subsequent vehicle (i.e., NESCCAF predicted that even without regulations, industry will be making some improvements to vehicles that could reduce CO_2 emissions and will increase their cost).

Table II-5. Potential Carbon Dioxide Emissions Reductions from Small Car (NESCCAF, 2004)

Small Car	Combined Technology Packages	CO_2 (g/mi)	Potential CO_2 reduction from 2002 baseline	Retail Price Equivalent 2002	Potential CO_2 reduction from 2009 baseline	Retail Price Equivalent 2009
Near Term 2009-2012	DVVL,DCP,A5 (2009 baseline)	284	-2.6%	$308	0%	$0
	DCP,CVT,EPS,ImpAlt	270	-7.6%	$570	-5.1%	$262
	DCP,A4,EPS,ImpAlt	269	-7.6%	$360	-5.2%	$52
	DCP,A5,EPS,ImpAlt	260	-10.7%	$494	-8.3%	$186
	DCP,A6	260	-10.8%	$346	-8.4%	$38
	DVVL,DCP,AMT,EPS,ImpAlt	233	-19.9%	$465	-17.8%	$157
	GDI-S,DCP,Turbo,AMT,EPS, ImpAlt	215	-26.4%	$1128	-24.4%	$820
Mid Term 2013-2015	gHCCI,DVVL,ICP,AMT,EPS,ImpAlt	229	-21.6%	$673	-19.6%	$365
	CVVL,DCP,AMT,ISG-SS,EPS, ImpAlt	216	-25.7%	$1387	-23.8%	$1079
	gHCCI,DVVL,ICP,AMT,ISG, EPS,eACC	204	-29.9%	$1570	-28.1%	$1262
Long Term 2015-	dHCCI,AMT,ISG,EPS,eACC	217	-25.5%	$2536	-23.5%	$2228
	ModHEV	213	-26.9%	$1937	-25.0%	$1629
	HSDI,AdvHEV	147	-49.5%	$5117	-48.2%	$4809
	AdvHEV	138	-52.6%	$3017	-51.4%	$2709

Notes: Costs are included here to place the technology benefits in context. Costs and their derivation are discussed in greater detail in section III; Reductions for all scenarios except the baseline include benefits listed in Table II-4 and benefits from improved air conditioning systems from NESCCAF (2004).

For the small car category, CO_2 reductions were greatest using a turbocharged engine that was downsized such that overall performance was maintained. Gasoline stoichiometric direct injection engine technology was also included in this package because it affords a higher compression ratio than would otherwise be possible in order to further reduce CO_2 emissions. Dual cam phasers provide additional flexibility relative to optimum intake and exhaust valve timing and the use of a six speed automated manual transmission, electric power steering and a more efficient alternator all contribute to lower vehicle CO_2 emissions as well. A lower cost runner-up approach in terms of CO_2 reductions for small cars was a package utilizing discrete variable valve lift and dual cam phasers that also affords some engine downsizing and reduced pumping losses, again combined with the same transmission and improved auxiliaries as the previous case. For this approach, there would be a small cost savings relative to the 2009 baseline. These packages achieved CO_2 reductions of about 20-26 percent relative to the 2002 baseline. For the mid-term, technologies that combine gasoline homogeneous charge compression ignition engines with or without an integrated starter generator plus use of electrical engine water pump and more could reduce CO_2 emissions approximately 22-30 percent. Instead of the 42 volt integrated starter generator, a lower cost 12 volt belt assisted start-stop starter-alternator system could also be incorporated, but with somewhat lower reductions in CO_2 emissions. In the longer term, use of diesel homogeneous charge compression ignition engines and hybrids could provide CO_2 reductions of approximately 26-50 percent.

Table II-6. Potential Carbon Dioxide Emissions Reductions from Large Car (NESCCAF, 2004)

Large Car	Combined Technology Packages	CO_2 (g/mi)	Potential CO_2 reduction from 2002 baseline	Retail Price Equivalent 2002	Potential CO_2 reduction from 2009 baseline	Retail Price Equivalent 2009
Near Term 2009-2012	DVVL,DCP,A6 (2009 baseline)	322	-6.6%	$427	0%	$0
	DCP,A6	304	-11.5%	$479	5.6%	$52
	DCP,CVT,EPS,ImpAlt	303	-12.1%	$708	-6.0%	$281
	CVVL,DCP,A6	290	-15.9%	$864	-10.0%	$437
	DCP,DeAct,A6	286	-16.9%	$662	-11.0%	$235
	DCP,Turbo,A6,EPS,ImpAlt	279	-19.2%	$266	-13.5%	-$161
	CVVL,DCP,AMT,EPS,ImpAlt	265	-23.2%	$873	-17.8%	$446
	GDI-S,DeAct,DCP,AMT,EPS, ImpAlt	265	-23.2%	$931	-17.8%	$504
	GDI-S,DCP,Turbo,AMT,EPS, ImpAlt	251	-27.2%	$369	-22.1%	-$58
Mid Term 2013-2015	gHCCI,DVVL,ICP,AMT,EPS,ImpAlt	272	-21.0%	$880	-15.5%	$453
	DeAct,DVVL,CCP,A6,ISG,EPS, eACC	259	-24.7%	$1721	-19.4%	$1294
	ehCVA,AMT,EPS,ImpAlt	250	-27.4%	$929	-22.2%	$502
	ehCVA,GDI-S,AMT,EPS,ImpAlt	242	-29.9%	$1188	-24.9%	$761
	gHCCI,DVVL,ICP,AMT,ISG,EPS, eACC	231	-32.9%	$1796	-28.2%	$1369
	GDI-S,Turbo,DCP,A6,ISG,EPS, eACC	224	-35.1%	$1196	-30.5%	$769
Long Term 2015-	dHCCI,AMT,ISG,EPS,eACC	277	-19.7%	$1978	-14.0%	$1551
	ModHEV	252	-27.0%	$2119	-21.8%	$1692
	AdvHEV	163	-52.6%	$3503	-49.3%	$3076
	HSDI,AdvHEV	157	-54.4%	$4728	-51.1%	$4301

Notes: Costs are included here to place the technology benefits in context. Costs and their derivation are discussed in greater detail in section III; Reductions for all scenarios except the baseline include benefits listed in Table II-4 and benefits from improved air conditioning systems from NESCCAF (2004).

For the large car class, a turbocharged engine approach similar to the one modeled in the small car class again provided maximum CO_2 reductions in the near term of about 22 percent. Since the base engine was a 6 cylinder design, staff assumed that downsizing to a 5 cylinder engine (for costing purposes) would maintain most of the smoothness of a V6 configuration and remain attractive to consumers. Even then, there was a projected savings relative to a 2009 baseline model. CO_2 emission reduction results of 17.8 percent were obtained (but at a small net cost relative to a 2009 baseline vehicle this time) using cylinder deactivation in conjunction with a gasoline stoichiometric direct injection engine with dual cam phasers (plus the same 6 speed automated manual transmission, electric power steering, and an improved efficiency alternator). Another similar performing package (17.8 percent CO_2 reduction) for the near term utilized continuously variable valve lift and dual cam phasers plus the same additional equipment at an additional cost in 2009 of $446. For the mid-term, a number of alternatives provide substantial reductions in CO_2 emissions. One of the more effective technology clusters includes electrohydraulic camless valve actuation in conjunction with gasoline stoichiometric direct injection plus the 6 speed automated manual transmission, electric power steering and more efficient alternator, yielding up to a 25 percent reduction in CO_2 emissions at a cost increment of $761 in 2009. To obtain even further reductions, integrated starter generators could also be utilized. Other combinations that could be used with integrated starter generators to achieve over a 30 percent reduction include gasoline homogeneous charge compression ignition engines and again turbocharged engines with gasoline direct injection systems. For the long term, moderate and advanced hybrids can achieve around 40-50 percent reductions in CO_2 emissions.

Table II-7. Potential Carbon Dioxide Emissions Reductions from Minivan (NESCCAF, 2004)

Minivan	Combined Technology Packages	CO_2 (g/mi)	Potential CO_2 reduction from 2002 baseline	Retail Price Equivalent 2002	Potential CO_2 reduction from 2009 baseline	Retail Price Equivalent 2009
Near Term 2009-2012	DVVL,CCP,A5 (2009 baseline)	370	-6.4%	$315	0%	$0
	DCP,A6	348	-12.0%	$671	-5.9%	$356
	GDI-S,CCP,DeAct,AMT,EPS, ImpAlt	328	-17.0%	$781	-11.2%	$466
	DVVL,CCP,AMT,EPS,ImpAlt	325	-17.7%	$494	-12.1%	$179
	CCP,AMT,Turbo,EPS,ImpAlt,	325	-17.8%	$1042	-12.2%	$727
	DeAct,DVVL,CCP,AMT,EPS, ImpAlt	317	-19.9%	$624	-14.4%	$309
	CVVL,CCP,AMT,EPS,ImpAlt	316	-20.2%	$916	-14.7%	$601
	GDI-S,DCP,Turbo,AMT,EPS, ImpAlt	307	-22.3%	$1397	-17.0%	$1082
Mid Term 2013-2015	ehCVA,GDI-S,AMT,EPS,ImpAlt	300	-24.1%	$1431	-18.9%	$1116
	GDI-S,CCP,AMT,ISG,DeAct,EPS, eACC	297	-25.0%	$1716	-19.8%	$1401
Long Term 2015-	dHCCI,AMT,EPS,ImpAlt	313	-20.8%	$1635	-15.3%	$1320
	Mod HEV	389	-26.8%	$2167	-21.8%	$1852
	Adv HEV	188	-52.6%	$3631	-49.3%	$3316

Notes: Costs are included here to place the technology benefits in context. Costs and their derivation are discussed in greater detail in section III; Reductions for all scenarios except the baseline include benefits listed in Table II-4 and benefits from improved air conditioning systems from NESCCAF (2004).

Essentially the same technologies emerged as most effective in reducing CO_2 emissions for the minivan as for the large car group.

Table II-8. Potential Carbon Dioxide Emissions Reductions from Small Truck (NESCCAF, 2004)

Small Truck	Combined Technology Packages	CO_2 (g/mi)	Potential CO_2 reduction from 2002 baseline	Retail Price Equivalent 2002	Potential CO_2 reduction from 2009 baseline	Retail Price Equivalent 2009
Near Term 2009-2012	DVVL,DCP,A6 (2009 baseline)	404	-9.0%	$427	0%	$0
	DCP,A6	379	-14.7%	$479	-6.3%	$52
	DCP,A6,Turbo,EPS,ImpAlt	371	-16.7%	$283	-8.4%	-$144
	DCP,A6,DeAct	366	-17.7%	$656	-9.5%	$229
	GDI-S,DCP,DeAct,AMT,EPS, ImpAlt	334	-24.9%	$928	-17.5%	$501
	DeAct,DVVL,CCP,AMT,EPS, ImpAlt	330	-26.2%	$736	-18.9%	$309
	GDI-S,DCP,Turbo,AMT,EPS, ImpAlt,DCP-DS	318	-28.4%	$367	-21.3%	-$60
Mid Term 2013-2015	DeAct,DVVL,CCP,A6,ISG,EPS, eACC	316	-29.0%	$1757	-22.0%	$1330
	ehCVA,GDI-S,AMT,EPS,ImpAlt	309	-30.5%	$1186	-23.6%	$759
	HSDI,AMT,EPS,ImpAlt	307	-31.0%	$1585	-24.2%	$1158
Long Term 2015-	dHCCI,AMT,EPS,ImpAlt	331	-25.6%	$912	-18.3%	$485
	Mod HEV	325	-27.0%	$2071	-19.7%	$1644
	Adv HEV	210	-52.7%	$3375	-48.0%	$2948

Notes: Costs are included here to place the technology benefits in context. Costs and their derivation are discussed in greater detail in section III; Reductions for all scenarios except the baseline include benefits listed in Table II-4 and benefits from improved air conditioning systems from NESCCAF (2004).

Once again, the same technology clusters that were most effective in reducing CO_2 emissions in the large car and minivan classes were also effective in the small truck class. Of interest, high speed direct injection diesel engines using the same driveline and accessory improvements didn't achieve significantly lower CO_2 emissions than the electrohydraulic camless valve actuation/gasoline direct injection system that was modeled in this class. This outcome is due largely to diesel fuel's relatively high carbon content that results in relatively higher CO_2 emissions. Given the higher cost of diesels and their attendant emission cleanup challenges, they are not necessarily clear CO_2 emission improvement strategies.

Table II-9. Potential Carbon Dioxide Emissions Reductions from Large Truck (NESCCAF, 2004)

Large Truck	Combined Technology Packages	CO_2 (g/mi)	Potential CO_2 reduction from 2002 baseline	Retail Price Equivalent 2002	Potential CO_2 reduction from 2009 baseline	Retail Price Equivalent 2009
Near Term 2009-2012	CCP,A6 (2009 baseline)	484	-5.5%	$126	0%	$0
	DVVL,DCP,A6	442	-13.6%	$549	-8.6%	$423
	CCP,DeAct,A6	433	-15.4%	$550	-10.5%	$424
	DCP,DeAct,A6	430	-15.9%	$916	-11.0%	$790
	DeAct,DVVL,CCP,A6,EHPS,ImpAlt	418	-18.4%	$779	-13.6%	$653
	DeAct,DVVL,CCP,AMT,EHPS, ImpAlt	396	-22.6%	$667	-18.1%	$541
Mid Term 2013-2015	CCP,DeAct,GDI-S, AMT,EHPS,ImpAlt	416	-18.6%	$872	-13.9%	$746
	DeAct,DVVL,CCP,A6,ISG, EHPS,eACC	378	-26.2%	$1710	-21.9%	$1584
	ehCVA,GDI-S,AMT,EHPS,ImpAlt	381	-25.5%	$1684	-21.2%	$1558
Long Term 2015-	GDI-L,AMT,EHPS,ImpAlt	354	-30.7%	$1901	-26.7%	$1775
	Mod HEV	372	-27.3%	$2340	-23.1%	$2214
	dHCCI,AMT,ISG,EPS,eACC	362	-29.3%	$3031	-25.2%	$2905
	GDI-L,AMT,ISG,EPS,ImpAlt	354	-30.7%	$2800	-26.7%	$2674
	HSDI,AdvHEV	244	-52.2%	$6821	-49.5%	$6695
	AdvHEV	241	-52.9%	$4091	-50.2%	$3965
Notes: Costs are included here to place the technology benefits in context. Costs and their derivation are discussed in greater detail in section III; Reductions for all scenarios except the baseline include benefits listed in Table II-4 and benefits from improved air conditioning systems from NESCCAF (2004).						

For large trucks, cylinder deactivation strategies in conjunction with flexible valve timing and lift strategies were the most effective in the near term, offering a CO_2 reduction of about 18 percent (also included 6 speed automated manual transmission, electrohydraulic power steering, and an improved alternator). Strategies relying on turbocharging and engine downsizing were avoided since large trucks may be more likely to encounter periods of sustained high load operation where cylinder pressures and temperature would be much higher than in non-turbo applications. In order to retain adequate engine durability under such conditions, significant engine upgrades would likely be needed, which were difficult to quantify. For the mid-term adding an integrated starter generator and electric engine water pump brought the potential CO_2 reduction to about 22%. Use of electrohydraulic camless valve actuation coupled with gasoline stoichiometric direct injection achieved about the same CO_2 reduction *without* an integrated starter generator. Use of the latter would improve the CO_2 reductions even more, though this was not specifically modeled. For the long term, gasoline lean burn direct injection or use of diesel multi-mode technology, both coupled with an integrated starter generator could allow about a 27 percent reduction in CO_2, but both technologies have aftertreatment issues remaining. Otherwise, moderate or aggressive hybrids that rely on a downsized engine coupled with an electric motor for assist could achieve around a 50 percent CO_2 reduction. However, some believe that the short lived motor assistance based on battery storage capacity would limit the attractiveness of such large truck hybrids when sustained high load operation might be more likely. Perhaps an approach such as in the Lexus RX400H, wherein the base engine stays constant and the hybrid system is added to boost short-term acceleration and significantly improve CO_2 emissions during normal driving, would be a better approach for large trucks.

B. MOBILE AIR CONDITIONING SYSTEM

1. Improved Air Conditioning Systems

Mobile air conditioning contributes to greenhouse gas emissions through “direct” refrigerant releases and “indirect” exhaust CO_2 emissions. Direct emissions are due to releases from vehicles through air conditioning system leakage (a slow process, sometimes called “regular emissions”), during accidents or other events that suddenly breach containment of the system refrigerant (sometimes called “irregular emissions”), during service events, and when vehicles are dismantled without proper recovery of the refrigerant. In new vehicles, the potential for reduction of direct emissions is considerable. Industry sources estimate that existing systems can be cost-effectively improved to achieve up to 50 percent reduction in refrigerant leakage, also referred to as "regular emissions." Strategies for reducing direct emissions and estimates of the corresponding emission reductions are presented in this section.

Although current emission certification testing procedures do not include operation of vehicle air conditioning systems, their operation contributes significantly to exhaust CO_2 emissions, also known as "indirect emissions." These emissions are largely attributed to the added load on the engine from operation of the air conditioning system. It has been estimated that CO_2 emission reductions from 30 to 50 percent may be achievable by reducing the engine load requirements of air conditioning systems. Potential measures for reducing indirect emissions are presented in this section. The associated emission reductions were estimated through vehicle simulation modeling performed by NESCCAF (2004).

2. Estimating Direct Emissions

Modern mobile air conditioning systems that enhance travel comfort and safety include features such as integrated cooling, heating, demisting, defrosting, air filtering, and humidity control. The basic components of a typical system are shown in Figure II-5.

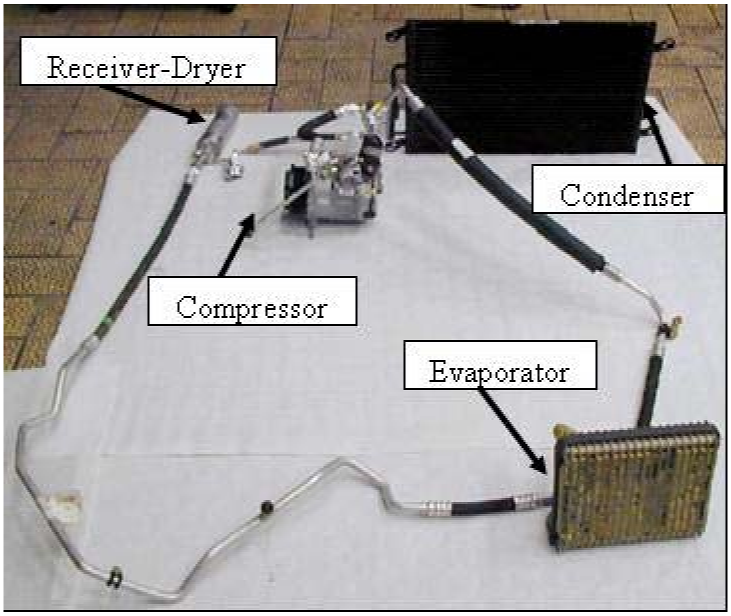


Figure II-5. Typical Mobile Air-Conditioning System Components (Clodic et al, 2003)

The current refrigerant in new vehicles is HFC-134a (1,1,1,2-tetrafluoroethane), which has a global warming potential (GWP) of 1,300. Direct lifetime emissions of HFC-134a from vehicular air conditioning systems in California have been estimated using a method developed by ARB staff based on 1) HFC-134a consumption data by nine government and commercial fleets, 2) surveys of 966 vehicle owners on their air conditioning system repair incidence, 3) data on repair incidence among 12,000 fleet vehicles in California, and 4) information from automobile dismantlers. The data were used to provide estimates of the averages of the parameters in a mass balance model that equates vehicular lifetime emissions to lifetime inputs of HFC-134a. The analysis yielded lifetime direct emissions of approximately 1.36 kg of HFC-134a for a typical vehicle in the current California fleet, which has a 16-year median lifetime. This is equivalent to emissions of 85 grams of HFC-134a per year of life per vehicle, although the emissions may not be uniform over the vehicle's life. The methodology for this estimate is presented in Appendix C.3. The limited data available suggest that about 72% of the lifetime refrigerant emissions are due to leakage (“regular emissions”), 22 percent are due to sudden or accidental releases (“irregular emissions”), and 6 percent are due to releases during dismantling. Assuming 200,000 lifetime miles driven, this breaks down into approximately 6 CO_2-equivalent grams per mile from “regular” emissions, 2 CO_2-equivalent grams per mile from “irregular” emissions and 0.5 CO_2-equivalent grams per mile from dismantling emissions.

3. Possible Measures to Reduce Direct Emissions

Reduction of direct emissions can be achieved through system improvements such as the use of low-permeability hoses and improved elastomer seals and connections. Work is in progress to define a component-specific blueprint for a baseline (current) air conditioning system and to identify key components for potential improvement (reduced leakage). It is anticipated that upgrades to a few key components (e.g., compressor shaft seal) would result in a low-leak system that can achieve a 50 percent reduction in “regular” emissions. However, improved containment would not reduce accidental releases or releases during scrapping. A 50 percent reduction in “regular” leakage emissions by a low-leak system translates into a reduction of approximately 3 CO_2-equivalent grams/mile, for an incremental increase in cost to the manufacturer of approximately twelve dollars [Appendix C.1]. Table II-10 illustrates the principal components of interest for upgrading to a low-leak system that halves "regular" emissions.

Table II-10. Preliminary components of interest in a low-leak HFC-134a air conditioning system.

Component	Approximate Contribution to Leakage Emissions
Flexible hose (high and low pressure) construction and dimensions	25%
System component connections (type and number)	25%
Compressor shaft seal	50%
Leakage emissions prior to component improvements	6 CO_2-equiv (g/mi)
50% Reduction in Leakage	**~3 CO_2-equiv (g/mi)**

While low-cost improvements to current systems for reducing refrigerant leakage appear feasible, the benefits for climate change are not particularly significant. Other alternatives can result in greater benefits. As mentioned earlier, HFC-134a is the current refrigerant in vehicles manufactured during and since the 1995 model year. HFC-134a has a GWP of 1,300. Emissions of HFC-134a could be avoided completely by using an alternative refrigerant with a lower GWP. The leading alternatives are HFC-152a (1,1-difluoroethane), with a GWP of 120, and CO_2, with a GWP defined as one. HFC-152a could be introduced as a vehicular refrigerant on a schedule that appears to be consistent with the requirements of AB 1493.

For systems equipped with HFC-152a, total refrigerant emissions would be reduced by 91 percent (on a CO_2-equivalent mass basis). However, since HFC-152a is mildly flammable under certain conditions, mitigation options are being considered. Specifically, industry representatives report that they are currently evaluating technical solutions for mitigating potential safety concerns associated with HFC-152a, including the use of charge evacuation technologies that could be invoked in vehicle crash situations. The schedule for which CO_2 systems could be deployed is uncertain. For systems that use CO_2, the relative global warming impact of refrigerant emissions would be virtually eliminated. Safety issues related to high system pressures and in-cabin releases are currently under evaluation.

Table II-11 presents estimates of emission reductions to be achieved from upgrading to a low-leak HFC-134a system, a low-leak HFC-152a system, and a carbon dioxide system. Note that it is only "regular" (leakage) emissions that would be impacted by the upgrade of a current HFC-134a system, not all the lifetime emissions. That is, approximately 72% of the lifetime emissions from a current HFC-134a system are due to leakage. For a low-leak system, the relative proportions of "regular", "irregular", "service events" and "dismantling" emissions are altered by factors consequential to reduced leakage (e.g. increase in "dismantling" emissions due to a larger refrigerant volume during dismantling). It is recommended that the reader consult Appendix C.3 (our emissions quantification appendix) for the methodology used to estimate emissions for low-leak systems.

A reduction of approximately 3 CO_2-equivalent grams per mile is estimated for upgrading to a low-leak HFC-134a system that achieves a 50 percent reduction in leakage. In contrast, the use of alternative refrigerants with lower GWPs can result in greater benefits because they reduce total lifetime emissions (i.e., regular, irregular, and end-of-life releases). For upgrading to a low-leak HFC-152a system or a CO_2 system, the benefits are approximately 8.5 or 9 CO_2-equivalent grams per mile, respectively.

Table II-11. Direct Climate Change Emissions from Baseline and Alternative Mobile Air Conditioning Systems

	Air Conditioning System			
	HFC-134a Baseline Technology	Low-Leak HFC-134a	Low-Leak Primary Expansion HFC-152a[1]	Carbon Dioxide[2]
Total refrigerant emissions (g/yr)	85	70	70	85
Total refrigerant emissions, in CO_2 eq. (g/mi)	9	7	0.7	0.007
Refrigerant leakage emissions, in CO_2 eq. (g/mi)	6	3	0.3	0.005
Reduction in CO_2 eq (g/mi)	**Baseline**	**3**	**8.5**	**9**

[1] *Assuming same mass leak rate as a low-leak HFC-134a system*
[2] *Assuming same mass leak rate as a baseline HFC-134a system*

4. Efforts by the European Union to Reduce Direct Emissions

In August of 2003, the European Commission advanced a proposal mandating the future phaseout of HFC-134a for vehicle air conditioning systems. Beginning in 2005, annual leakage rates would be limited for refrigerants with a GWP of 150 or higher. Effectively, this action targets reductions for HFC-134a. A system of credits was also proposed that would ultimately accomplish a phaseout by 2019 of any refrigerant with a GWP of 150 or higher (Meszler, 2004). At the time of this report, the direction of the proposed regulation appears to be shifting towards elimination of a credit system and a future ban for new vehicles with a refrigerant having a GWP greater than 50. This would remove HFC-152a as a refrigerant option, and require substitution with other refrigerants, such as CO_2 or hydrocarbons. While there are significant advantages to substitution with CO_2, including the fact that it has the lowest GWP of the leading technologies, there are also disadvantages. Some characteristics of CO_2 air conditioning systems are: 1) significantly higher pressures and associated leak tendency, 2) high component costs, 3) new service training would be needed, 4) an internal heat exchanger would be necessary, 5) lower performance at higher ambient temperature conditions, and 6) timing for deployment is uncertain. More details can be found in Appendix C.1.

The European Union regulation is not final, and the ultimate outcome remains uncertain. However, because both the European Union and the United States each comprise about one third of worldwide vehicle sales, it is likely that there will be some uniformity in air conditioning system design. Note that the European Union's efforts did not result in a proposal to address indirect emissions due to a lack of consensus on how to address these emissions.

5. Possible Measures to Reduce Indirect Emissions

The contribution of mobile air conditioning systems to exhaust CO_2 (indirect) emissions can be attributed to transportation of the unit's mass and operation of the system. It is estimated that reducing the engine load requirements from air conditioning systems can reduce these emissions up to 50 percent. This can be accomplished by utilizing more efficient variable displacement compressors (VDC) with better control systems, and condensers and evaporators with improved heat transfer.

The engine load requirements for externally controlled VDCs are lower than those of fixed displacement compressors (FDCs) because, rather than providing a constant flow of refrigerant with on/off cycling, VDCs with appropriate controls modulate compressor displacement, allowing refrigerant flow to vary to meet cooling demands. As cooling demands increase, the benefits of VDCs decrease relative to those of FDCs. For the limited conditions that require maximum compressor displacement, the benefit of VDCs over FDCs approaches zero.

VDCs are a currently available technology. Though not yet commonly employed in the United States, VDCs are more prevalent in the European Union. The on/off cycling associated with FDCs noticeably impacts the driveability of smaller engines. Consequently, in the European Union, where the average engine displacement is less than two liters, VDCs provide significant improvement to engine driveability.

Another means to enhance air conditioning system operation is to reduce the amount of outside air admitted to the passenger compartment relative to recirculated air. This reduces the amount of hot air from outside that needs to be cooled by the system. This strategy can be applied to either manually or automatically controlled air conditioning systems and is also currently feasible.

Additionally, performance can be improved by the elimination of "air reheat". A characteristic of air conditioning systems equipped with FDCs is the tendency in mild conditions to overcool and then reheat the air to provide a moderate level of cooled air. Because VDCs modulate refrigerant flow, they can be adapted to eliminate air reheat. However, because elimination of air reheat requires automatic climate controls, and manual controls are most prevalent in the United States, this feature was not assumed for modeling the benefits of improved vehicle air conditioning systems (Meszler, 2004).

As mentioned previously, substitution with the refrigerant HFC-152a appears to have significant near-term potential for reducing CO_2-equivalent emissions associated with the refrigerant. In addition, because HFC-152a transfers heat slightly more efficiently than HFC-134a, there are also gains to be made with HFC-152a substitution from a CO_2 emission reduction (indirect emissions) standpoint. While the driving force behind substitution with HFC-152a may be the reduction in direct emissions, the likelihood of near-term implementation is favorable and therefore the indirect benefits were included in the vehicle simulation modeling.

Other air conditioning system CO_2 reduction strategies aim to reduce the vehicle solar load. Use of solar reflective glass, modified glass angles, improved cabin insulation, altering interior and exterior colors, and other measures can significantly reduce the solar load and consequently ease the engine load from air conditioning systems. However, these strategies are independent of air conditioning design and were not incorporated into the simulation modeling. In the future, benefits from these types of measures may be credited through the incorporation of whole vehicle testing that simulates solar load. However, presently such testing is neither reliable nor accurate, and needs further development.

Vehicle simulation modeling was performed to estimate the CO_2 benefits from the use of an improved air conditioning system for each of the five vehicle classes. Details of the modeling inputs are provided in Appendix C.4. Given the considerations discussed in this section, operation with a conventional FDC was compared to that of a system comprised of a VDC with external controls, air reuse strategy, and substitution with HFC-152a refrigerant. Results are presented in Table II-12 and have been adjusted to reflect data from an extensive study by the National Renewable Energy Laboratory (NREL). This study indicates that within California, vehicle air conditioning is operated for cooling or demisting during 29% of the vehicle miles traveled (Johnson, 2002; Rugh and Hovland, 2003). Consequently, failure to adjust the modeling results would have overestimated the benefits of upgrading the air conditioning system.

Table II-12. Indirect CO_2 Emissions from Baseline and Improved Mobile Air Conditioning Systems

		Vehicle class				
		Small Car	Large Car	Minivan	Small Truck	Large Truck
Emissions (g/mi)	With no A/C system operation	277.9	329.2	376.4	425.7	492.6
	With baseline A/C system[1]	291.4	344.6	395.4	444.7	511.6
	Due to baseline air conditioning	13.5	15.4	19.0	19.0	19.0
	With improved A/C system[2]	284.4	336.6	385.6	434.9	501.8
Reductions Due To Improved A/C System	(g/mi)	7.0	8.0	9.8	9.8	9.8
	In A/C emissions	52%	52%	52%	52%	52%
	From baseline A/C system	2.4%	2.3%	2.5%	2.2%	1.9%

[1] *Utilizes fixed displacement compressor*
[2] *Equipped with a variable displacement compressor, air recirculation, and HFC-152a as the refrigerant*

For upgrading to a VDC with external controls, air recirculation, and HFC-152a as the refrigerant, the estimated indirect emission reduction is 7 CO_2–equivalent grams per mile for a small car, 8 CO_2–equivalent grams per mile for a large car, and 9.8 CO_2–equivalent grams per mile for minivans, small trucks, and large trucks.

C. ALTERNATIVE FUEL VEHICLES

This section of the assessment investigates the potential to reduce tailpipe and upstream climate change emissions with increased usage of alternative-fuel vehicles. The alternative-fuel vehicles discussed in this section are all available today in limited quantities. Relative to gasoline vehicles, they provide reduced climate change tailpipe emissions and reduced upstream emissions associated with manufacture, storage and distribution of fuels. In order of effectiveness in reducing climate change emissions, staff is considering the benefits of vehicles that use the following fuels:

- Electricity
- Hydrogen
- Liquified Petroleum Gas (LPG)
- Natural Gas (CNG)
- Alcohol fuels: Ethanol & Methanol

Some of the emission reduction technologies cited in other sections of this document are applicable to alternative-fuel vehicles. These technologies would further reduce climate change emissions from these vehicles. ARB staff may be evaluating further additional benefits when these technologies are applied to alternative-fuel vehicles, including the synergistic effects. However, such an evaluation would take place only in those instances when it is likely that the emission reductions would be cost effective relative to conventional vehicles.

1. Electricity

Both electricity and hydrogen are unique among alternative fuels in that they are quite easily converted from hydrocarbon fuel feedstocks and energy sources into a transportation fuel. They are also the only alternative fuels that have the potential to be generated from renewable resources which results in zero upstream emissions.

Battery electric vehicles (BEVs) have the largest potential to reduce climate change emissions relative to any other alternative-fuel vehicle or conventional technology option under consideration. These vehicles can provide 50% or greater emission reductions, dependent upon how the electricity used by these vehicles is produced. Unfortunately, building and marketing cost-effective “full function” BEVs that would be direct replacements for existing light-duty vehicles remains a significant challenge. With near-term cost projections and technology options, only small neighborhood and “City” BEVs have the potential to be built at attractive enough prices to be viable in the near future (Anderman et al, 2000). ARB staff estimates a City EV cost to be appoximately 1/3 of the cost of a full size BEV.

Grid-connected hybrid electric vehicles (HEVs) have the ability to operate on battery power alone for some distance, typically 20-60 miles. Once the battery is depleted, these vehicles use a conventional internal combustion engine. Grid-connected HEVs have a smaller battery pack than pure BEVs and correspondingly lower incremental vehicle cost. Research into grid-connected HEVs indicates that this combination of technologies could be viable in the marketplace later in this decade.

While the emission benefits are lower for grid-connected HEVs than for BEVs, grid-connected HEVs have the potential to reduce greenhouse emissions beyond "strong" conventional hybrids, achieving climate change emissions reductions of 40% or more, depending on battery size and electricity source. The necessary research that will lead to improvements in battery technology has shifted towards higher specific-power hybrid vehicle applications. Many of the anticipated improvements may also benefit the performance of higher specific-energy batteries for grid-connected HEVs and increase their viability in the post-2009 timeframe (EPRI, 2001).

2. Hydrogen

As stated above hydrogen is quite easily converted from hydrocarbon fuel feedstocks and energy sources into a transportation fuel. Hydrogen also has the potential to be generated from renewable resources which would result in zero upstream emissions.

Hydrogen fuel cell vehicles provide emission reductions of 50% or greater relative to conventional vehicles. The most likely near-term method of producing hydrogen is steam-reformation of natural gas. Staff's preliminary estimates indicate that this method would result in a reduction in greenhouse gas emissions of over 50 percent relative to conventional vehicles.

Hydrogen internal combustion engine vehicles also offer significant potential for climate change emission reductions as their climate change tailpipe emissions are near zero and the upstream emissions are the equivalent to those from hydrogen fuel cell vehicles.

Availability of cost-effective vehicles and lack of fueling infrastructure make hydrogen fuel cell and internal combustion engine vehicles extraordinarily challenging for consideration in the 2009 timeframe. However, to the degree that auto manufacturers choose to produce hydrogen fuel cell vehicles or hydrogen internal combustion engine vehicles, the benefits will be large.

3. Alcohol Fuels (Ethanol and Methanol)

Relative to other conventional vehicles, alcohol fuel vehicles do provide moderate greenhouse gas emission benefits. Based on discussions with representatives from TIAX, LLC and Argonne National Laboratory it is likely that vehicles that run on either ethanol or methanol could reduce greenhouse gas emission by between 1% and 2% for each 10% of conventional gasoline displaced.

Currently, approximately 2% of new vehicles sold in California are capable of running on a blend of up to 85% ethanol and 15% gasoline. Almost all of these vehicles use primarily, if not exclusively, conventional fuel. The reason for this is the lack of fueling infrastructure, cost associated with ethanol, and fuel availability. Staff is not considering allowing these types of flexible fuel vehicles to be used to meet the requirements of the Climate Change regulations. However, dedicated alcohol fuel vehicles would be considered and staff is in the process of quantifying the extent to which these vehicles provide emission benefits.

4. Liquid Petroleum Gas (LPG)

According to representatives from TIAX, LLC and results of the Argonne National Laboratory GREET model 1.6, on a full fuel cycle basis, LPG vehicles provide approximately a 30% greenhouse gas emission benefit relative to conventional vehicles. LPG is widely used in dedicated LPG vehicles with more than 33,000 vehicles operating in California alone. It is popular in fleet applications where central refueling is possible, and is the most cost-effective alternative fuel available at the present time.

5. Natural Gas (CNG)

According to representatives from TIAX, LLC and results of the Argonne National Laboratory GREET model 1.6, natural gas vehicles (NGVs) provide approximately a 30% greenhouse gas emission benefit relative to conventional vehicles when they are equipped with catalysts to reduce CH_4 emissions. Recent studies have shown that the high CH_4 emissions of NGVs can be significantly reduced through improved catalysts (natural gas fuel is typically about 90% methane). Specifically, increasing the cell density of the catalyst while maintaining the same level of precious metal loading can reduce emissions of both oxides of nitrogen NO_x and CH_4. Since NGVs have inherently lower CO_2 emissions than gasoline vehicles, manufacturers may be encouraged to incorporate improved catalyst technology on their NGVs.

Methane and nitrous oxide have relatively high global warming potentials and are products of either the combustion process of fuel in the case of methane, or a byproduct of the catalytic process in the case of nitrous oxide. Natural gas vehicles emit relatively high levels of methane due to the high methane content of the fuel. While difficult to control, catalyst modifications have been demonstrated to reduce methane emissions from these vehicles. Similarly, catalyst improvements may also reduce nitrous oxide emissions.

One of the most significant challenges with the use of other alternative fuels is the need for the infrastructure to distribute and facilities to dispense the fuel. Electricity and natural gas have a significant advantage over other alternative fuels because a distribution infrastructure is already in place so that these fuels are available at most homes in California. This existing fuel infrastructure would allow drivers of these vehicles to refuel at home and could greatly improve the marketability of home-refuelable vehicles.

Table II-13. Potential Carbon Dioxide Equivalent Emissions Reductions with Alternative Fuel Vehicle Technologies for Passenger Cars

Vehicle type	Exhaust CO_2 equivalent emissions (g/mi)	Upstream CO_2 equivalent emissions (g/mi)	Total CO_2 emissions (g/mi)	Lifetime CO_2 equivalent emissions (ton)	Lifetime CO_2 equivalent emissions reduced from 2002 baseline[5] (ton)	Percent reduction of CO_2 equivalent emissions from 2002 baseline
Conventional vehicles[1]	311	98	409	91	0.0	0%
Compressed natural gas (CNG) [2,3]	205	75	280	65	25.5	-28%
Liquified natural gas (LNG) [2]	tbd	tbd				
Liquid propane gas (LPG) [2]	240	35	275	64	26.7	-29%
Plug-in Hybrid [2]	65	130	195	45	45.3	-50%
Ethanol (E85) [2]	60	190	250	58	32.5	-36%
Hydrogen combustion [2,4]	13	185	198	46	44.6	-49%

[1] numbers for conventional vehicle baseline use approximated California sales-weighted average of baseline vehicle emission from small car and large car classes from above and 24% upstream CO_2 equivalent estimate; [2] Unnasch, 2004; [3] CNG vehicle assumed to have catalyst equipment; [4] Compressed hydrogen from steamed reformed natural gas; [5] based on EMFAC number for average vehicle lifetime (See Appendix B)

D. EXHAUST CATALYST IMPROVEMENT

Potential reduction of passenger vehicle greenhouse gas contribution could result from improved exhaust catalysts to reduce emissions of methane (CH_4) and nitrous oxide (N_2O). Both of these gases, although their mass emissions are much less than CO_2 emissions from vehicles, have significant overall contributions to global climate change. Each of these gases, due to their distinct chemical properties, impacts the atmospheric energy balance differently than CO_2, such that a ton of CH_4 in the atmosphere is thought to have the same net warming effect over 100 years as 23 tons of CO_2. Emissions of N_2O have an even more potent effect on the atmosphere, with an estimated effect 296 times greater than CO_2.

Methane is a component of the unburned hydrocarbons emitted by motor vehicles. Since it has a very low potential to form ozone in the atmosphere, vehicular CH_4 emissions are not specifically regulated. Methane emissions are generally proportional to vehicle hydrocarbon (HC) and non-methane organic gas (NMOG) emissions. However, as NMOG fleet average emissions approach near-zero levels by 2010 (i.e., 0.035 grams/mile for passenger cars), CH_4 emissions are also expected to be extremely low. The expected CH_4 emission rates for 2009 vehicles less than 8,500 lbs is 0.005 grams/mile (EMFAC, 2003).

Nitrous oxide emissions are a by-product of a vehicle's aftertreatment catalyst and are primarily formed during catalyst warm-up. Similar to CH_4 emissions, N_2O emissions are generally proportional to vehicle oxides of nitrogen (NO_x) emissions. In addition, as fleet average NO_x emissions approach near-zero levels by 2010, N_2O emissions are also expected to be extremely low. Since it is not specifically a regulated pollutant, catalyst manufacturers are not currently pursuing strategies to reduce vehicle N_2O emissions. However, inclusion of N_2O emissions in the proposed vehicle climate change regulations may encourage more development work if a cost-effective solution can be identified.

Table II-14 shows estimates of the total contribution of N_2O and CH_4 emissions to the climate change emission inventory for average light-duty vehicles. Although it is conceivable that these emissions could be reduced through faster catalyst heating at vehicle start-up and enhanced catalyst systems with either higher surface density or higher and/or revised catalyst loadings, staff is not aware of such efforts at this time.

Table II-14. Contribution of Nitrous Oxides and Methane to Vehicle Climate Change Emissions

	Nitrous oxide (N_2O)	Methane (CH_4)
Emission rate[1] (g/mi)	0.006	0.005
Global warming impact (GWP)	296	23
Lifetime CO_2 equivalent emissions (tons/vehicle)	0.4	0.03

[1] *Emission rates based on EMFAC, 2003 estimates for the 2019 vehicle fleet*

E. SUMMARY OF TECHNOLOGY ASSESSMENT RESULTS

For the purpose of providing perspective regarding the various sources of CO_2 equivalent emissions that have been covered in this report, Table II-15 itemizes the various contributions of CO_2 equivalent emissions and provides a total inventory. The table also provides an indication of the degree of reduction that an ARB climate change emission regulation could achieve.

Table II-15. Summary of Technology Options and Potential Reductions

Vehicle/Fuel System	Climate Change Emission	Average lifetime GHG contribution (ton CO_2 equiv.)	Percent of lifetime GHG contribution	Technologies available for GHG reduction	Maximum percent GHG reduction studied here
Exhaust emissions	Carbon dioxide	100.6	73.90%	Engine, drivetrain, alternative fuels technologies	up to 60%
	Nitrous Oxide	0.4	0.29%	Improved exhaust catalyst	negl.
	Methane	0.03	0.02%	Improved exhaust catalyst	negl.
Fuel-Delivery "Upstream"	CO_2, N_2O, and CH_4	31.8	23.36%	Alternative fuels	up to 80%
Refrigerant leakage	Hydrofluorocarbons (HFCs)	3.30	2.43%	Tighter A/C system, R-152	Up to 95%
Total		136.13	100.0%		

III. COST EFFECTIVENESS OF TECHNOLOGIES

This section quantifies the cost-effectiveness of the technologies of Section II in reducing climate change emissions in an effort to determine whether or not the regulation at various levels of proposed climate change emission reductions would be cost effective. Climate change emission reduction cost-effectiveness is measured as the initial incremental cost to consumers for the climate change reduction technology divided by the total lifetime carbon dioxide equivalent ton reduction ($/ton). Estimating this cost per ton includes a collection of data on annual and lifetime vehicle usage, and the costs of the technologies.

Using California Department of Motor Vehicle (DMV) data on annual mileage records, as used in the EMFAC model, the median vehicle life and annual average mileage of California vehicles were determined. For both the representative small and large cars, the median vehicle life was found to be 16 years, and the median number of miles at vehicle retirement was found to be about 202,000 miles. For the representative minivan, small truck, and large truck, which are all classified as category 2 light-duty trucks (LDT2), the median vehicle traveled approximately 224,000 miles over 19 years. See Appendix B, Table B-1 for average vehicle miles traveled during each year.

The initial cost is the incremental cost of the climate change reduction technology, or package of technologies. These technology costs are discussed for specific technologies in the sections below. Along with the initial cost of the new technology, there are additional mark-up costs to account for the profit and overhead for the companies that research, develop, and manufacture those technology components. Our analysis uses a 40% rate mark-up rate, i.e. each of the technology costs are multiplied by 1.4 to determine their retail price equivalents. This is between the conventionally utilized RPE multipliers for general environmental technology assessments of 1.26 (EPA, 2004) and research studies of particular vehicle components with factors of 1.5 and above (Vyas, et al, 2000).

A. ENGINE, DRIVETRAIN, AND HYBRID-ELECTRIC VEHICLE TECHNOLOGIES

Estimations for the incremental cost to the manufacturer for each of the technologies considered here were primarily taken from those supplied by Martec for the NESCCAF (2004) study. In so doing, the assessment assures coordination and consistency between costs and emission reductions associated with the exact same technology clusters, with inclusion of the secondary cost effects that the technologies cause to other subsystems on-board the vehicle.

Some of the key aspects of the methodology used in the NESCCAF report for determining the costs of the engine and drivetrain technologies are summarized here. For further documentation see NESCCAF (2004). The main source of the price estimates were field interviews with representatives from automotive and component manufacturing industries that are involved with the engineering, production, product planning, and purchasing of new technologies. The costing assumes long term learned out production volumes of at least 500,000 units for each of the technologies, and assumes a highly competitive purchasing environment including several suppliers.

However, some deviations were made from the Martec cost estimates. For some of the emerging technologies, Martec did not account for additional cost reductions resulting from unforeseen innovations in design and manufacturing. While this may be adequate for technologies that are well defined and primarily mechanical in nature, staff believes that further cost reductions for emerging technologies that incorporate electromechanical and electronic components are highly probable. Based on our experience in the Low Emission Vehicle program, it is inevitable that consolidation of parts and further simplifications in production processes will take place when volumes reach into the millions per year per supplier and numerous suppliers are competing. The prices that ARB projects normally reflect components that have become commodity items. One example is the dramatic cost reductions for consumer electronic devices a few years after the first ones go on sale. Another example is the reduction in costs from initial estimates for emission control components developed by manufacturers for Low-Emission Vehicles. For example, there were projections of the need for multiple close-coupled catalysts to meet the SULEV emission levels when the Low Emission Vehicle program was adopted and yet we now have one manufacturer utilizing only one underfloor catalyst to meet these emission levels.

Usually, ARB estimates themselves tend to be high when high volume production is achieved. The Martec costs for these emerging technologies we believe will ultimately cost less in high volume production due to improvements from innovative design changes and manufacturing techniques. Accordingly, they have been discounted by 30%, consistent with ARB's experience in estimating costs in the Low Emission Vehicle program. In discussions with some suppliers, it was their opinion that such costs might be reduced as much as 50% depending on the level of utilization of the part at present and the type of system in which it is utilized.

In addition, ARB staff reduced the cost of converting from an overhead valve engine to a dual overhead cam system by the cost of the aluminum block that was included by Martec. Although manufacturers may switch to an aluminum block when making such a changeover, staff believes it is not a necessary step to accomplish the conversion. Manufacturers may utilize an aluminum block to save weight or perhaps for competitive marketing reasons, or others. Staff, therefore, reduced the conversion cost by $250 for a V-6 engine and $300 for a V-8 engine relative to Martec's estimates. For cylinder deactivation, Martec indicated that they did not include cost for controlling driveline noise when in the cylinder deactivation mode since the systems to accomplish this were in a state of flux. Staff included an additional $50 for a long term solution that involves modifications to the current exhaust system rather than inclusion of a special valve in the exhaust or active engine mounts since at least one vehicle in current production utilizes the more simple approach successfully. Further, ARB staff has conducted its own independent analysis of hybrid-electric vehicle technologies (See Appendix A), and those cost estimations are included in this analysis. ARB staff continues to assess costs with individual suppliers, and in those cases where we find that the Martec estimates might not contain the latest information, revisions will be made in our final report. The staff solicits additional cost input at the workshop from others wishing to provide such information, either in the open forum or confidentially. Table III-1 lists the estimated RPE costs of the individual technologies considered by this study.

Table III-1. Estimated Cost of Individual Technologies

Technologies	Vehicle Class				
	Small car	Large car	Minivan	Small truck	Large truck
	Retail Price Equivalent ($)				
Intake Cam Phasing	49	98	49	98	49
Exhaust Cam Phasing	49	98	49	98	49
Dual Cam Phasing (DCP)	98	196	388	196	409
Coupled Cam Phasing (CCP)	70	161	49	161	49
Discrete Variable Valve Lift (DVVL,ICP)	154	259	210	259	259
Discrete Variable Valve Lift (DVVL,DCP)	203	357	549	357	619
Discrete Variable Valve Lift (DVVL,CCP)	175	322	210	322	259
Continuous Variable Valve Lift (CVVL,ICP)	259	483	626	483	764
Continuous Variable Valve Lift (CVVL,DCP)	280	581	773	581	911
Continuous Variable Valve Lift (CVVL,CCP)	308	546	626	546	764
Electromagnetic Camless Valve Actuation (emCVA)	676	764	1078	764	1274
Electrohydraulic Camless Valve Actuation (ehCVA)	564	637	882	637	1078
Turbocharging (Turbo)	560	(150)	490	(150)	-
Cylinder Deactivation (DeAct)	-	183	183	183	217
Cylinder Deactivation (DeAct,DVVL)	-	266	266	266	325
Cylinder Deactivation (DeAct,DVVL,ICP)	-	364	315	364	374
Cylinder Deactivation (DeAct,DVVL,DCP)	-	462	635	462	524
Cylinder Deactivation (DeAct,DVVL,CCP)	-	427	315	427	374
Variable Charge Motion (CBR)					
Gasoline Direct Injection - Stochiometric (GDI-S)	189	259	259	259	294
Gasoline Direct Injection - Lean-Burn Stratified (GDI-L)	728	959	1043	1057	1554
Gasoline Homogeneous Compression Ignition (gHCCI)	560	840	840	-	-
Diesel – HSDI	2100	1225	2152	1260	2943
Diesel – Advanced Multi-Mode	1323	735	1310	568	1791
4-Speed Automatic Transmission	0	0	0	0	0
5-Speed Automatic	140	140	140	140	140
6-Speed Automatic	70	105	105	105	112
6-Speed Automated Manual	0	0	0	0	0
Continuously Variable Transmission (CVT)	210	245	245	245	-
12-volt 2kW BAS (Start Stop)	280	-	-	-	-
42-Volt 10 kW ISG (Start Stop)	609	609	609	609	659
42-Volt 10 kW ISG (Motor Assist)	902	902	902	902	902
Electric Power Steering (EPS)	20	39	39	39	-
Electro-Hydraulic Power Steering (E-HPS)	-	-	-	-	60
Improved Alternator (Higher efficiency)	56	56	56	56	56
Electric Water Pump (EWP)	70	70	70	70	70
Improved AC	88	88	88	88	88

Listed below in Tables III-2 through III-6, are the incremental cost to the manufacturer and the RPE cost to the consumer for the technology combinations modeled for each vehicle class. Again these technologies are separated into near-, mid-, and long-term according to their relative readiness for potential widespread market penetration. The package costs listed here include credit for the elimination of duplicate technologies such as the exhaust gas recirculation (EGR) valve that can be eliminated when using variable valve timing or cam phasing, elimination of the conventional starter and alternator when using ISG systems, or engine downsizing when using turbocharging.

Note that these costs are relative to the incremental cost for the 2009 baseline vehicle in each vehicle class. Each of the technology packages, along with the technologies listed, also includes the improved variable-displacement compressor air-conditioning systems, aggressive shift logic, improved rolling resistance tires, and engine friction reduction technologies.

Table III-2. Estimated Incremental Costs for Carbon Dioxide Reduction Technologies for Small Car Relative to 2009 Baseline

Small Car	Combined Technology Packages	Technology cost ($)	Retail Price Equivalent ($)
Near Term 2009-2012	DCP,EPS,A4,ImpAlt	37	52
	DCP,CVT,EPS,ImpAlt	187	262
	DVVLd,A5 (2009 baseline)	0	0
	DCP,A6	27	38
	DCP,A5,EPS,ImpAlt	133	186
	DVVL,DCP,AMT,EPS,ImpAlt	112	157
	GDI-S,DCP,Turbo,AMT,EPS,ImpAlt	586	820
Mid Term 2013-2015	gHCCI,DVVLi,AMT,EPS,ImpAlt	261	365
	gHCCI,DVVL,ICP,AMT,ISG,EPS,eACC	901	1262
	CVVL,DCP,AMT,ISG-SS,EPS,ImpAlt	771	1079
Long Term 2015-	ModHEV	1164	1629
	dHCCI,AMT,ISG,EPS,eACC	1591	2228
	AdvHEV	1935	2709
	HSDI,AdvHEV	3435	4809

Table III-3. Estimated Incremental Costs for Carbon Dioxide Reduction Technologies for Large Car Relative to 2009 Baseline

Large Car	Combined Technology Packages	Technology cost ($)	Retail Price Equivalent ($)
Near Term 2009-2012	DCP,A6	37	52
	DCP,CVT,EPS,ImpAlt	201	281
	DVVL,DCP,A6 (2009 baseline)	0	0
	CVVL,DCP,A6	312	437
	DCP,DeAct,A6	168	235
	DCP,Turbo,A6,EPS,ImpAlt	(161)	(161)
	CVVL,DCP,AMT,EPS,ImpAlt	319	446
	GDI-S,DeAct,DCP,AMT,EPS,ImpAlt	360	504
	GDI-S,DCP,Turbo,AMT,EPS,ImpAlt	(58)	(58)
Mid Term 2013-2015	gHCCI,DVVL,ICP,AMT,EPS,ImpAlt	324	453
	DeAct,DVVL,CCP,A6,ISG,EPS,eACC	924	1294
	ehCVA,AMT,EPS,ImpAlt	359	502
	ehCVA,GDI-S,AMT,EPS,ImpAlt	544	761
	gHCCI,DVVL,ICP,AMT,ISG,EPS,eACC	978	1369
	GDI-S,Turbo,DCP,A6,ISG,EPS,eACC	549	769
Long Term 2015-	dHCCI,AMT,42V,EPS,eACC	1108	1551
	ModHEV	1209	1692
	AdvHEV	2197	3076
	HSDI,AdvHEV	3072	4301

Table III-4. Estimated Incremental Costs for Carbon Dioxide Reduction Technologies for Minivan Relative to 2009 Baseline

Minivan	Combined Technology Packages	Technology cost ($)	Retail Price Equivalent ($)
Near Term 2009-2012	DVVL,CCP,A5 (2009 baseline)	0	0
	DCP,A6	254	356
	GDI-S,CCP,DeAct,AMT,EPS,ImpAlt	333	466
	DVVL,CCP,AMT,EPS,ImpAlt	128	179
	CCP,AMT,Turbo,EPS,ImpAlt	519	727
	DeAct,DVVL,CCP,AMT,EPS,ImpAlt	221	309
	CVVL,CCP,AMT,EPS,ImpAlt	429	601
	GDI-S,DCP,Turbo,AMT,EPS,ImpAlt	773	1082
Mid Term 2013-2015	GDI-S,CCP,AMT,ISG,DeAct,EPS,eACC	1001	1401
	ehCVA,GDI-S,AMT,EPS,ImpAlt	797	1116
Long Term 2015-	ModHEV	1323	1852
	AdvHEV	2369	3316
	dHCCI,AMT,EPS,ImpAlt	943	1320

Table III-5. Estimated Incremental Costs for Carbon Dioxide Reduction Technologies for Small Truck Relative to 2009 Baseline

Small Truck	Combined Technology Packages	Technology cost ($)	Retail Price Equivalent ($)
Near Term 2009-2012	DCP,A6	37	52
	DVVL,DCP,A6 (2009 baseline)	0	0
	DCP,A6,Turbo,EPS,ImpAlt	(144)	(144)
	DCP,A6,DeAct	164	229
	GDI-S,DCP,Turbo,AMT,EPS,ImpAlt, DCP-DS	(60)	(60)
	DeAct,DVVL,CCP,AMT,EPS,ImpAlt	221	309
	GDI-S,DCP,DeAct,AMT,EPS,ImpAlt	358	501
Mid Term 2013-2015	DeAct,DVVL,CCP,A6,ISG,EPS, eACC	950	1330
	ehCVA,GDI-S,AMT,EPS,ImpAlt	542	759
	HSDI,AMT,EPS,ImpAlt	827	1158
Long Term 2015-	ModHEV	1174	1644
	AdvHEV	2106	2948
	dHCCI,AMT,EPS,ImpAlt	346	485

Table III-6. Estimated Incremental Costs for Carbon Dioxide Reduction Technologies for Large Truck Relative to 2009 Baseline

Large Truck	Combined Technology Packages	Technology cost ($)	Retail Price Equivalent ($)
Near Term 2009-2012	CCP,A6 (2009 baseline)	0	0
	DVVL,DCP,A6	302	423
	CCP,DeAct,A6	303	424
	DCP,DeAct,A6	564	790
	DeAct,DVVL,CCP,A6,EHPS,ImpAlt	466	653
	DeAct,DVVL,CCP,AMT,EHPS,ImpAlt	386	541
Mid Term 2013-2015	CCP,DeAct,GDI-S, AMT,EHPS,ImpAlt	533	746
	DeAct,DVVL,CCP,A6,ISG,EPS, eACC	1131	1584
	ehCVA,GDI-S,AMT,EHPS,ImpAlt	1113	1558
Long Term 2015-	GDI-L,AMT,EHPS,ImpAlt	1268	1775
	dHCCI,AMT,ISG,EPS,eACC	2075	2905
	ModHEV	1581	2214
	AdvHEV	2832	3965
	HSDI,AdvHEV	4782	6695
	GDI-L,AMT,42V,EPS,ImpAlt	1901	2674

Figures III-1 through III-5 show the results of the cost-effectiveness assessments of each technology package for the five different vehicle types. These figures plot each packages' cost-effectiveness versus the resulting greenhouse gas reduction from the technology packages. These determinations are based on the information provided in this interim document and do not necessarily represent the final values to be recommended by staff. The data points have been shaped differently to denote their expected market readiness. Near-term technology packages are diamonds, mid-term are triangles, and long-term are "X"s. More detailed results in tabular form are summarized at the end of the section in Table III-10.

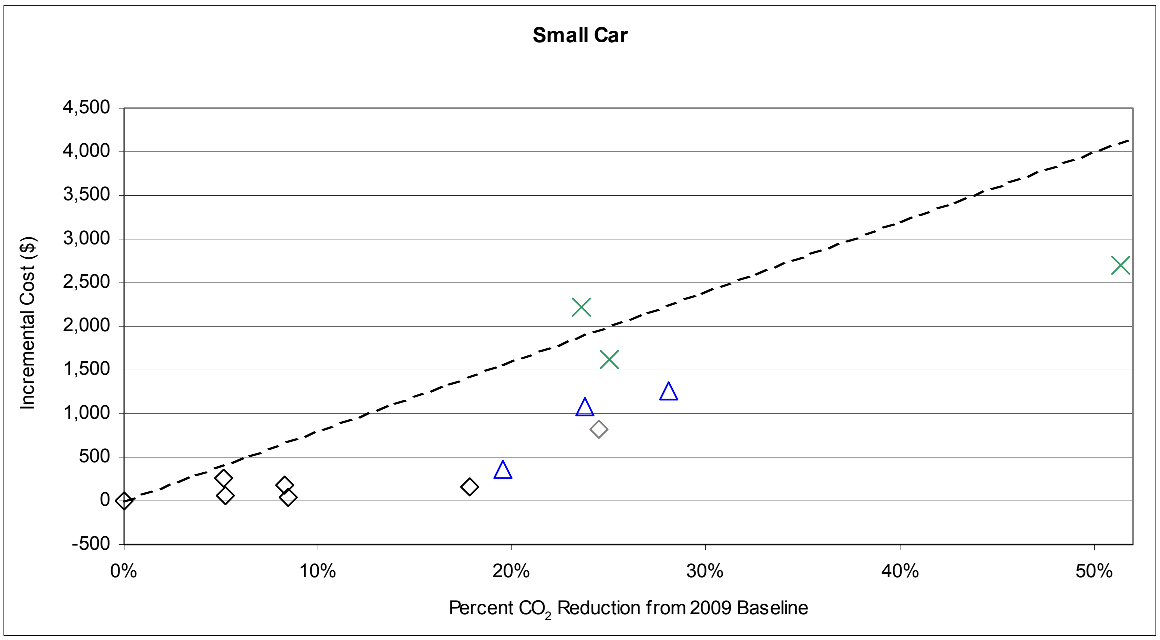


Figure III-1. Cost Effectiveness for Technology Packages on 2009 Baseline Small Cars

For the small cars (See Figure III-1), all of the near-term technologies have cost-effectiveness ratios less than or equal to $50 per ton of lifetime CO_2 reduced. Of these near-term technologies, the maximum reduction technology package was the one with a turbocharged stoichiometric gasoline direct injection (GDI-S) engine with dual cam phasing (DCP) and an automated manual transmission (AMT), and various other technology improvements. This package yielded a 22% CO_2 emission reduction for an additional cost of about $600 from the 2009 small car baseline, for a $44 per ton CO_2 emission reduction. The next highest near-term package CO_2 reduction came from discrete variable valve lift (DVVL), dual cam phasing (DCP), and an automated manual transmission (AMT). This package yielded a 16% CO_2 reduction with a negligible cost-effectiveness ratio with respect to the 2009 baseline small car cost. The highest mid-term technology scenario for small cars included homogeneous combustion compression ignition (HCCI) technology and offered a 26% CO_2 emission. Some of the longer-term (beyond 2009) technologies, like advanced hybrid-electrics and diesels, resulted in higher potential CO_2 reductions, but had cost-effectiveness ratios between $100 and $150 per ton for small cars.

For large cars (See Figure III-2), all of the near-term technology scenarios resulted in cost-effectiveness ratios of less than $50/ton. The maximum reduction from a near-term technology was from the turbocharged stoichiometric gasoline direct injection (GDI-S) engine with dual cam phasing (DCP), and an automated manual transmission (AMT). This package yielded a 20% reduction in exhaust CO_2 emissions for a cost comparable with the 2009 baseline large car technology package. The maximum reduction mid-term technology package in the analysis had a very similar technology package – a turbocharged stoichiometric gasoline direct injection (GDI-S) engine with dual cam phasing (DCP), a 6-speed automatic transmission (A6), and also had an integrated starter generator (ISG). This package yielded a 29% reduction in exhaust CO_2 emissions for an increased initial cost of about $750 from the 2009 large car baseline with a $28 per ton cost-effectiveness.

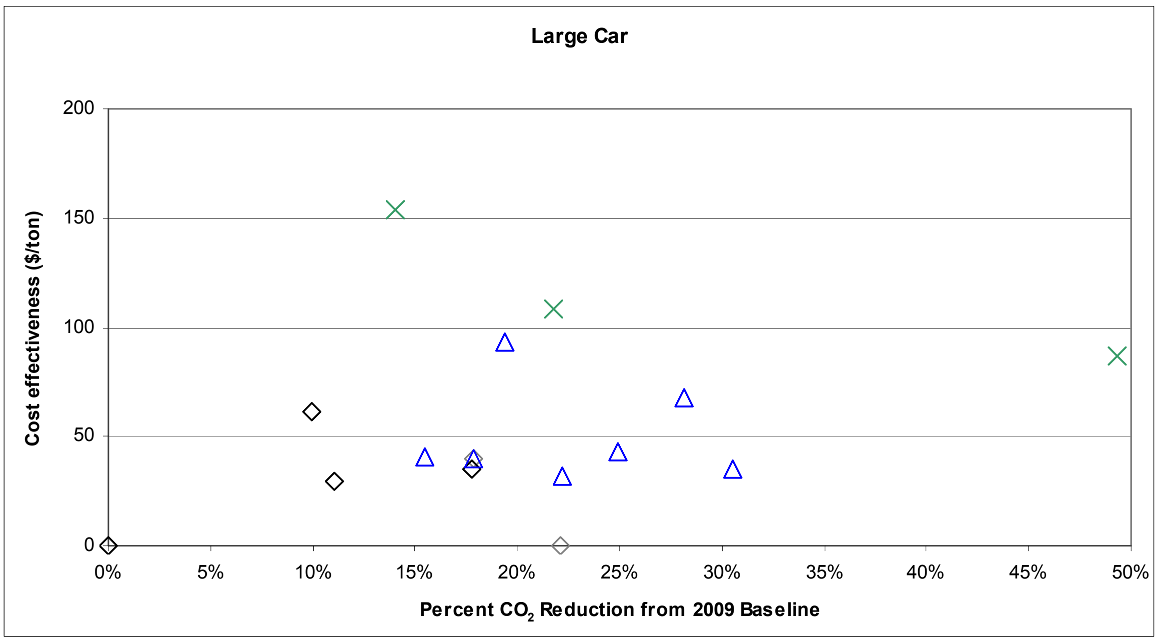


Figure III-2. Cost Effectiveness for Technology Packages on 2009 Baseline Large Cars

For the minivan (See Figure III-3), the maximum reduction from a near-term technology package in the analysis was determined to be the stoichiometric gasoline direct injection (GDI-S) engine with coupled cam phasing (CCP), and an automated manual transmission (AMT). This package yielded a 17% reduction in exhaust CO_2 emissions for an increased initial cost of about $1,000 from the 2009 large car baseline and a $56 per ton lifetime CO_2 reduced. A similar package that also included cylinder deactivation (DeAct) and a 42-volt integrated starter-generator (ISG) resulted in a 20% CO_2 reduction, $1,200 initial cost, and $66 per ton cost-effectiveness.

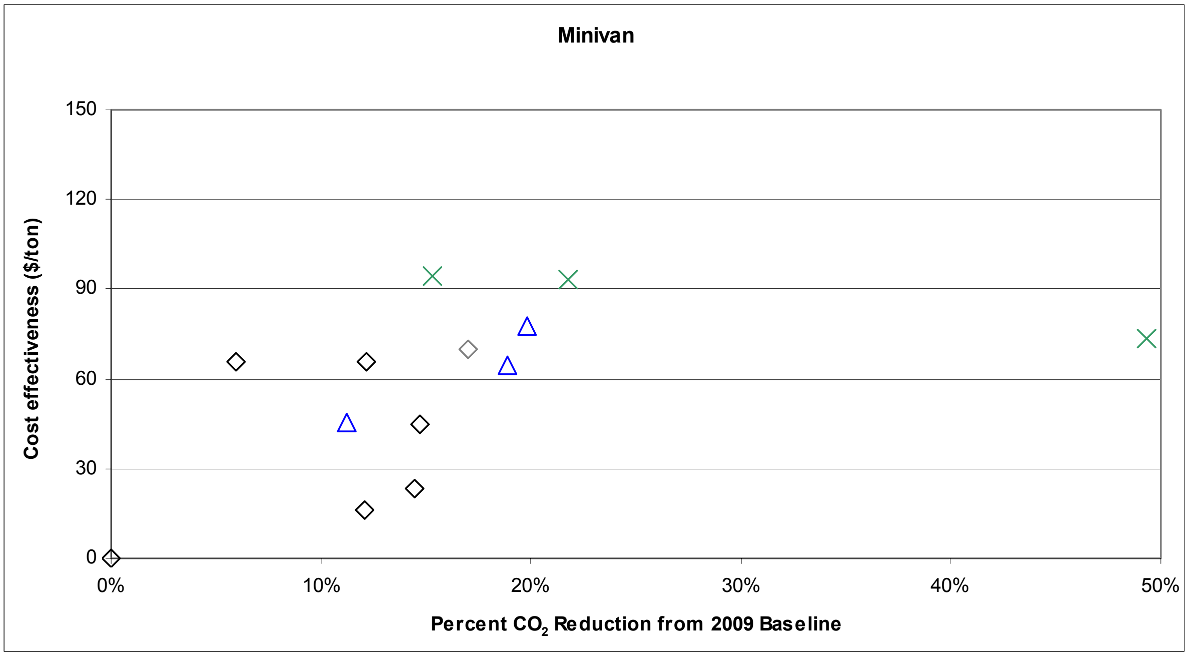


Figure III-3. Cost Effectiveness for Technology Packages on 2009 Baseline Minivans

For the small truck vehicle type (See Figure III-4), the near-term scenarios all had very low cost-effectiveness ratios of less than $30 per ton CO_2 emission reduction. The near-term scenario with turbocharging, stoichiometric gasoline direct-injection, dual cam phasing (DCP), and an automated manual transmission (AMT), yielded a cost-effective 19% reduction in exhaust CO_2 emissions, with little or no additional cost over the 2009 baseline. The stoichiometric gasoline direct-injection engine with electrohydraulic camless valve actuation and an automated manual transmission (AMT) offered a 22% CO_2 emission reduction at $26 per ton.

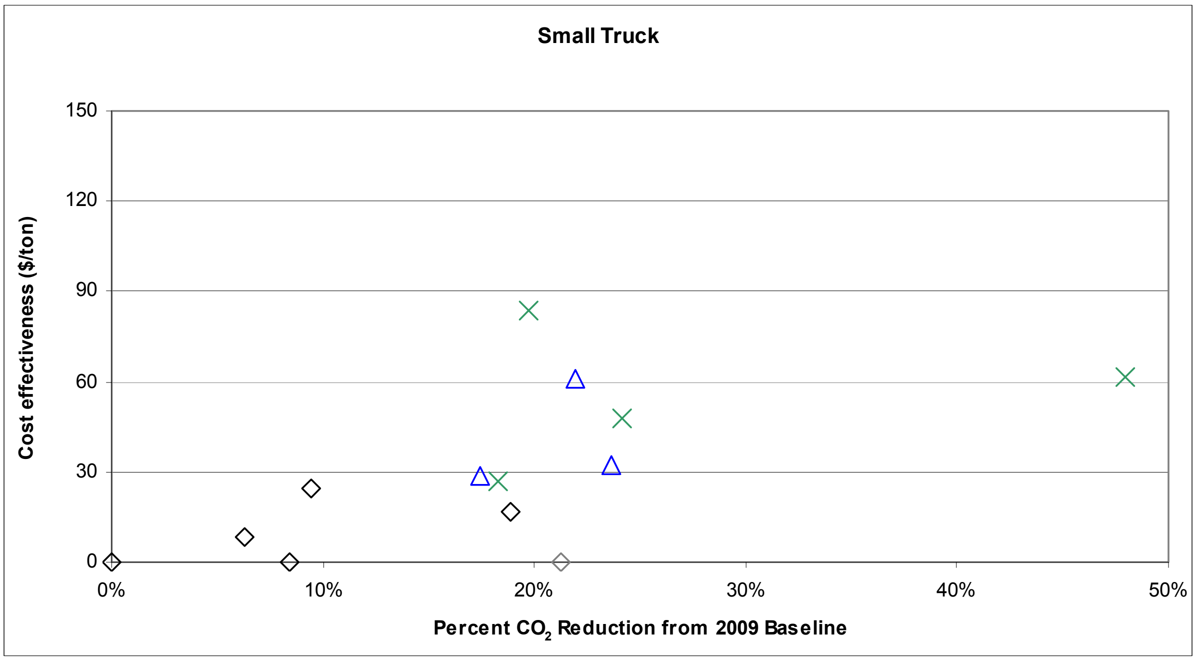


Figure III-4. Cost Effectiveness for Technology Packages on 2009 Baseline Small Trucks

For the large trucks (See Figure III-5), the maximum reduction near- and mid-term scenario packages involved cylinder deactivation, coupled cam phasing, and variable valve lift. The near-term version, which included an automated manual transmission (AMT), had a 16% CO_2 emission reduction relative to the 2009 baseline vehicle with a $17 per ton CO_2 reduction cost-effectiveness. The more advanced version of this package also included a 42-volt integrated starter-generator (ISG) and had a 20% CO_2 reduction with a $1,600 incremental cost from the 2009 large car baseline and a $58 per ton CO_2 reduction cost-effectiveness.

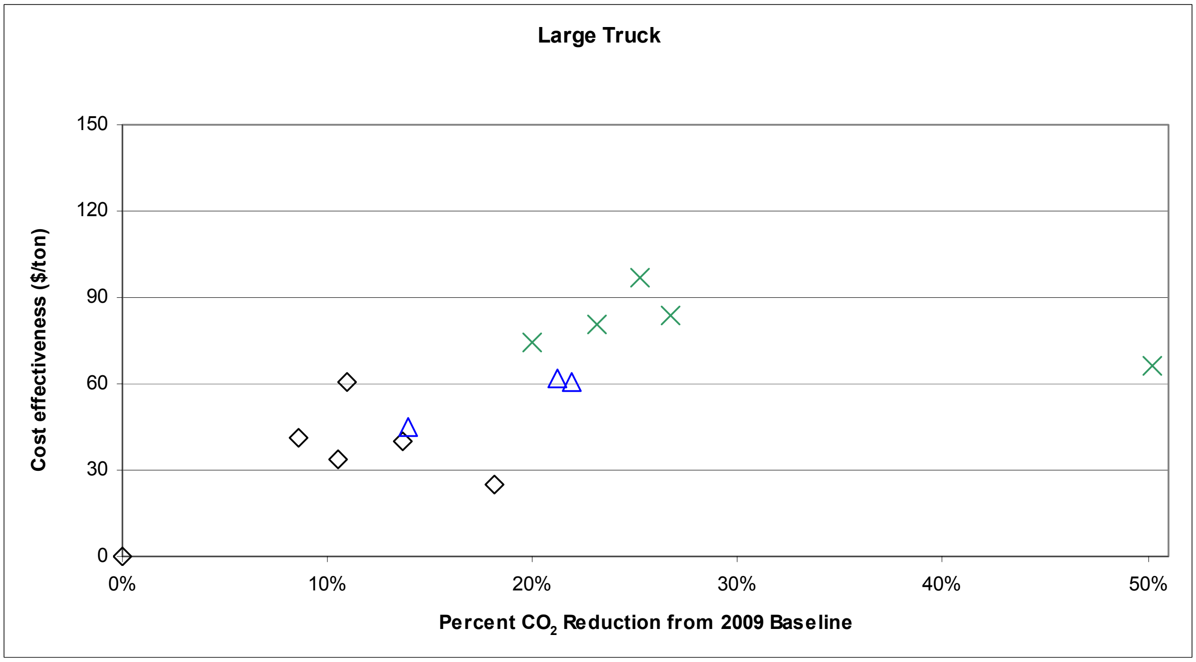


Figure III-5. Cost Effectiveness for Technology Packages on 2009 Baseline Large Trucks

C. ALTERNATIVE FUEL VEHICLES

The analysis of the potential cost-effectiveness of deploying alternative fuel vehicles to reduce greenhouse gases is ongoing. In this section alternative fuel vehicles are compared with their conventional baseline gasoline counterparts. This analysis of alternative fuel vehicles is similar to that of the cost-effectiveness analysis of the engine and drivetrain technologies above, but it also includes the reduction of upstream emissions. Also, for this analysis, comprehensive data on how alternative fuel technologies differ among different vehicle types (e.g. small cars and large trucks) were not available. Our baseline conventional vehicle is the California-specific sales weighting of the 2009 baseline small and large cars (i.e. trucks, minvans, etc. are excluded). Incremental retail costs associated with equipping the vehicles to operate on alternative fuels were researched by the ARB staff. These costs are shown in Table III-7. Applying the same vehicle use characteristics (VMT/yr, vehicle lifetime), the cost-effectiveness of the vehicle alternatives was evaluated.

Table III-7. Incremental Cost and Cost Effectiveness of Alternative Fuel Passenger Cars

Vehicle type	Lifetime CO_2 equivalent emissions (ton)	Lifetime CO_2 equivalent emissions reduced from 2002 baseline (ton)	Percent reduction from conventional gasoline vehicle	Incremental technology cost ($)	Cost effectiveness ($/ton)
Conventional vehicles	91	0.0	0%	0	
Compressed natural gas (CNG)	65	25.5	-28%	3600	141
Liquified natural gas (LNG)				tbd	-
Liquid propane gas (LPG)	64	26.7	-29%	700	26
Plug-in Hybrid	45	45.3	-50%	5700	126
Ethanol (E85)	58	32.5	-36%	0	0
Hydrogen Combustion	46	44.6	-49%	tbd	-

D. SUMMARY OF COST-EFFECTIVENESS ASSESSMENT

Technology improvements to vehicles' engine, drivetrain, and air-conditioning systems all result in potential cost-effective reductions of climate change emissions from light-duty vehicles. Improvements in the air conditioning system that included an improved variable displacement compressor, reduced leakage systems, and the use of an alternative refrigerant (HFC-152a) resulted in cost-effective CO_2 equivalent emission reductions of approximately $30 to $40 per ton for each vehicle class. Likewise cost-effective CO_2 reductions were found in various other vehicle technologies, as shown in Table III-8. The table summarizes the key findings for the cost-effectiveness assessment of engine, drivetrain, and hybrid-electric vehicle technologies. The table summarizes for each technology package the results for exhaust CO_2 emissions, the percentage change from the 2009 baseline emissions, the retail price estimations, and the cost-effectiveness for the installation of these technology packages on light-duty vehicles of the five vehicle classes that were studied here. There is a near-term, or off-the-shelf, technology package in each of the vehicle classes that resulted in a reduction of CO_2 emissions of at least 15-20% from baseline 2009 values with a cost-effectiveness ratio of less than $20 per ton. In addition, there is generally also a near-term technology package in each of the vehicle classes that results in an about 25% CO_2 emission reduction with a cost-effectiveness ratio of less than $60 per lifetime ton CO_2 emission reduction.

Table III-8. Summary of Cost-Effectiveness Parameters for Climate Change Emission Reduction Engine, Drivetrain, and Hybrid-Electric Vehicle Technologies

Vehicle Class	Combined Technology Packages	Technology readiness	CO_2 emissions (g/mi)	CO_2 change from 2002 baseline	Lifetime CO_2 reduced from 2002 baseline (ton)	CO_2 change from 2009 baseline	Lifetime CO_2 reduced from 2009 baseline (ton)	Retail cost incremental (2004$)	Cost incremental from 2009 baseline (2004$)	Lifetime Net Present Value (2004$)	Payback period (yr)	Average vehicle lifetime CO_2 reduction (ton)	Initial cost per lifetime CO_2 reduced ($/ton)
Small car	DVVL,DCP,A5	Near-term	284	-2.6%	1.7	0.0%	0.0	308	0	0	0	0.0	0
	DCP,A6	Near-term	260	-10.8%	7.0	-8.4%	5.3	346	38	635	1	5.3	7
	DCP,EPS,ImpAlt	Near-term	269	-7.6%	4.9	-5.2%	3.3	360	52	363	2	3.3	16
	DCP,A5,EPS,ImpAlt	Near-term	260	-10.7%	6.9	-8.3%	5.3	494	186	479	3	5.3	35
	DCP,CVT,EPS,ImpAlt	Near-term	269	-7.6%	4.9	-5.1%	3.2	570	262	149	8	3.2	81
	DVVL,DCP, AMT,EPS,ImpAlt	Near-term	233	-19.9%	12.9	-17.8%	11.3	465	157	1,267	2	11.3	14
	gHCCI,DVVL, ICP,AMT,EPS,ImpAlt	Mid-term	229	-21.6%	14.0	-19.5%	12.3	673	365	1,194	3	12.3	30
	GDI-S,DCP,Turbo, AMT,EPS,ImpAlt	Near-term	215	-26.4%	17.1	-24.4%	15.4	1,128	820	1,133	5	15.4	53
	gHCCI,DVVL,ICP, AMT,ISG,EPS,eACC	Mid-term	204	-29.9%	19.4	-28.1%	17.7	1,570	1,262	984	7	17.7	71
	dHCCI,AMT, ISG,EPS,eACC	Long-term	217	-25.5%	16.5	-23.5%	14.9	2,536	2,228	482	12	14.9	150
	HSDI,AdvHEV	Long-term	147	-49.5%	32.1	-48.2%	30.4	5,117	4,809	-396	>16	30.4	158
	CVVL,DCP,AMT, ISG-SS,EPS,ImpAlt	Mid-term	216	-25.7%	16.7	-23.8%	15.0	1,387	1,079	822	7	15.0	72
	Advanced HEV (ARB)	Long-term	138	-52.6%	34.1	-51.4%	32.5	3,017	2,709	1,401	8	32.5	83
	Moderate HEV (ARB)	Long-term	213	-26.9%	17.5	-25.0%	15.8	1,937	1,629	370	12	15.8	103
Large car	DVVL,DCP,A6	Near-term	322	-6.6%	5.1	0.0%	0.0	427	0	0	0	0.0	0
	DCP,DeAct,A6	Near-term	286	-16.9%	12.9	-11.0%	7.9	662	235	764	3	7.9	30
	CVVL,DCP,A6	Near-term	290	-15.9%	12.2	-10.0%	7.2	864	437	469	6	7.2	61
	DCP,A6	Near-term	304	-11.9%	9.1	-5.6%	4.0	479	52	459	1	4.0	13
	DCP,Turbo,A6,EPS,ImpAlt	Near-term	279	-19.2%	14.7	-13.5%	9.6	266	-161	1,381	0	9.6	0
	CVVL,DCP,AMT,EPS,ImpAlt	Near-term	265	-23.2%	17.8	-17.8%	12.7	873	446	1,166	3	12.7	35
	gHCCI,DVVL, ICP,AMT,EPS,ImpAlt	Long-term	272	-21.0%	16.1	-15.5%	11.1	880	453	949	4	11.1	41
	GDI-S,DCP,Turbo, AMT,EPS,ImpAlt	Near-term	251	-27.2%	20.9	-22.1%	15.8	369	-58	2,060	0	15.8	0
	DCP,CVT,EPS,ImpAlt	Near-term	303	-12.1%	9.3	-6.0%	4.3	708	281	259	6	4.3	66
	GDI-S,Turbo,DCP, A6,ISG,EPS,eACC	Mid-term	224	-35.1%	26.9	-30.5%	21.9	1,196	769	2,000	3	21.9	35
	DeAct,DVVL,CCP, A6,ISG,EPS,eACC	Mid-term	259	-24.7%	19.0	-19.4%	13.9	1,721	1,294	466	10	13.9	93
	gHCCI,DVVL,ICP, AMT,ISG,EPS,eACC	Mid-term	231	-32.9%	25.2	-28.2%	20.2	1,796	1,369	1,187	7	20.2	68
	dHCCI,AMT,ISG, EPS,eACC	Long-term	277	-19.7%	15.1	-14.0%	10.1	1,978	1,551	779	9	10.1	154
	HSDI,AdvHEV	Long-term	157	-54.4%	41.7	-51.1%	36.6	4,728	4,301	936	12	36.6	117
	GDI-S,DeAct,DCP, AMT,EPS,ImpAlt	Mid-term	265	-23.2%	17.8	-17.8%	12.8	931	504	1,111	4	12.8	39
	CVAeh,AMT,EPS,ImpAlt	Mid-term	250	-27.4%	21.0	-22.2%	15.9	929	502	1,514	3	15.9	32
	CVAeh,GDI-S, AMT,EPS,ImpAlt	Mid-term	242	-29.9%	22.9	-24.9%	17.8	1,188	761	1,497	4	17.8	43
	Advanced HEV (ARB)	Long-term	163	-52.6%	40.4	-49.3%	35.3	3,503	3,076	1,394	9	35.3	87
	Moderate HEV (ARB)	Long-term	252	-27.0%	20.7	-21.8%	15.6	2,119	1,692	284	12	15.6	108

Table III-8 (cont.) Summary of Cost-Effectiveness Parameters for Climate Change Emission Reduction Engine, Drivetrain, and Hybrid-Electric Vehicle Technologies

Vehicle Class	Combined Technology Packages	Technology readiness	CO2 emissions (g/mi)	CO2 change from 2002 baseline	Lifetime CO2 reduced from 2002 baseline (ton)	CO2 change from 2009 baseline	Lifetime CO2 reduced from 2009 baseline (ton)	Retail cost incremental (2004$)	Cost incremental from 2009 baseline (2004$)	Lifetime Net Present Value (2004$)	Payback period (yr)	Average vehicle lifetime CO2 reduction (ton)	Initial cost per lifetime CO2 reduced ($/ton)
Minivan	DVVL,CCP,A5	Near-term	370	-6.4%	6.3	0.0%	0.0	315	0	0	0	0.0	0
	DCP,A6	Near-term	348	-12.0%	11.7	-5.9%	5.4	671	356	307	7	5.4	66
	DVVL,CCP,AMT, EPS,ImpAlt	Near-term	325	-17.7%	17.3	-12.1%	11.0	494	179	1,174	2	11.0	16
	CVVL,CCP,AMT, EPS,ImpAlt	Near-term	316	-20.2%	19.7	-14.7%	13.4	916	601	1,044	5	13.4	45
	GDI-S,DCP,Turbo, AMT,EPS,ImpAlt	Near-term	307	-22.3%	21.8	-17.0%	15.5	1,397	1,082	819	8	15.5	70
	DeAct,DVVL,CCP, AMT,EPS,ImpAlt	Near-term	317	-19.9%	19.4	-14.4%	13.2	624	309	1,305	2	13.2	23
	GDI-S,CCP,DeAct, AMT,EPS,ImpAlt	Mid-term	328	-17.0%	16.5	-11.2%	10.3	781	466	792	5	10.3	45
	CCP,AMT,Turbo, EPS,ImpAlt	Near-term	325	-17.8%	17.4	-12.2%	11.1	1,042	727	633	7	11.1	66
	dHCCI,AMT, EPS,ImpAlt	Long-term	313	-20.8%	20.2	-15.3%	14.0	1,635	1,320	1,678	6	14.0	94
	GDI-S,CCP,AMT,ISG, DeAct,EPS,eACC	Mid-term	297	-25.0%	24.3	-19.8%	18.1	1,716	1,401	816	9	18.1	78
	CVAeh,GDI-S, AMT,EPS,ImpAlt	Mid-term	300	-24.1%	23.5	-18.9%	17.2	1,431	1,116	999	7	17.2	65
	Advanced HEV (ARB)	Long-term	188	-52.6%	51.2	-49.3%	44.9	3,631	3,316	2,197	8	44.9	74
	Moderate HEV (ARB)	Long-term	289	-26.8%	26.1	-21.8%	19.9	2,167	1,852	585	12	19.9	93
Small truck	DVVL,DCP,A6	Near-term	404	-9.0%	9.9	0.0%	0.0	427	0	0	0	0.0	0
	DCP,A6	Near-term	379	-14.7%	16.1	-6.3%	6.2	479	52	713	1	6.2	8
	DCP,A6,Turbo, EPS,ImpAlt	Near-term	371	-16.7%	18.3	-8.4%	8.4	283	-144	1,169	0	8.4	0
	DCP,A6,DeAct	Near-term	366	-17.7%	19.3	-9.5%	9.4	656	229	928	2	9.4	24
	GDI-S,DCP,Turbo, AMT,EPS,ImpAlt	Near-term	318	-28.4%	31.1	-21.3%	21.2	367	-60	2,663	0	21.2	0
	DeAct,DVVL,CCP, AMT,EPS,ImpAlt	Near-term	328	-26.2%	28.7	-18.9%	18.8	736	309	1,997	2	18.8	16
	DeAct,DVVL,CCP, A6,ISG,EPS,eACC	Mid-term	316	-29.0%	31.8	-22.0%	21.9	1,757	1,330	1,354	6	21.9	61
	GDI-S,DCP,DeAct, AMT,EPS,ImpAlt	Mid-term	334	-24.9%	27.3	-17.5%	17.4	928	501	1,633	3	17.4	29
	dHCCI,AMT, EPS,ImpAlt	Long-term	331	-25.6%	28.1	-18.3%	18.2	912	485	3,101	2	18.2	27
	HSDI,AMT, EPS,ImpAlt	Long-term	307	-31.0%	34.0	-24.2%	24.1	1,585	1,158	3,052	3	24.1	48
	CVAeh,GDI-S, AMT,EPS,ImpAlt	Mid-term	309	-30.5%	33.5	-23.6%	23.6	1,186	759	2,130	3	23.6	32
	Advanced HEV (ARB)	Long-term	210	-52.7%	57.7	-48.0%	47.8	3,375	2,948	2,920	7	47.8	62
	Moderate HEV (ARB)	Long-term	325	-27.0%	29.5	-19.7%	19.6	2,071	1,644	764	10	19.6	84
Large truck	CCP,A6	Near-term	484	-5.5%	6.9	0.0%	0.0	126	0	0	0	0.0	0
	DVVL,CCP,A6	Near-term	442	-13.6%	17.1	-8.6%	10.2	549	423	829	2	10.2	21
	DCP,DeAct,A6	Near-term	430	-15.9%	20.0	-11.0%	13.1	916	790	816	4	13.1	39
	CCP,DeAct,A6	Near-term	433	-15.4%	19.4	-10.5%	12.5	550	424	1,112	1	12.5	11
	DeAct,DVVL,CCP, A6,EHPS,ImpAlt	Near-term	418	-18.4%	23.1	-13.6%	16.2	779	653	1,340	2	16.2	23
	DeAct,DVVL,CCP, AMT,EHPS,ImpAlt	Near-term	396	-22.6%	28.5	-18.1%	21.6	667	541	2,106	1	21.6	12
	GDI-L,AMT, EHPS,ImpAlt	Long-term	387	-24.4%	30.7	-20.0%	23.8	1,901	1,775	1,148	7	23.8	66
	DeAct,DVVL,CCP, A6,ISG,EPS,eACC	Mid-term	378	-26.2%	33.0	-21.9%	26.1	1,710	1,584	1,620	5	26.1	50
	dHCCI,AMT,ISG, EPS,eACC	Long-term	362	-29.3%	36.9	-25.2%	30.0	3,031	2,905	781	11	30.0	90
	HSDI,AdvHEV	Long-term	244	-52.2%	65.8	-49.5%	58.9	9,474	9,348	-1,119	>19	58.9	155
	GDI-L,AMT,ISG, EPS,ImpAlt	Long-term	354	-30.7%	38.7	-26.7%	31.8	2,800	2,674	1,230	9	31.8	77
	CVAeh,GDI-S, AMT,EHPS,ImpAlt	Mid-term	381	-25.5%	32.1	-21.2%	25.2	1,684	1,558	3,099	4	25.2	53
	CCP,DeAct,GDI-S, AMT,EHPS,ImpAlt	Mid-term	416	-18.6%	23.5	-13.9%	16.6	872	746	1,288	3	16.6	28
	Advanced HEV (ARB)	Long-term	241	-52.9%	66.7	-50.2%	59.8	4,091	3,965	3,372	7	59.8	63
	Moderate HEV (ARB)	Long-term	372	-27.3%	34.4	-23.1%	27.5	2,340	2,214	1,162	8	27.5	73

IV. LIFETIME COST OF TECHNOLOGIES TO VEHICLE OWNER-OPERATOR

Following the direction of AB 1493 to demonstrate maximum cost-effective greenhouse gas reductions that are "economical to an owner or operator of a vehicle, taking into account the full life-cycle costs of a vehicle," this portion of the assessment provides estimations of the lifetime impact to vehicle operators for the greenhouse gas reduction technologies that were described previously.

Applying estimations for the technology costs and assumptions for vehicle use and economic variables, estimations of the lifetime vehicle costs are quantified using a net present value (NPV) framework. This section conducts an NPV analysis on the engine, drivetrain, hybrid-electric, and alternative fuel vehicle technologies that were described in the technology section. The ARB staff is currently investigating ways to integrate the MAC cost-effectiveness work presented in the previous section with the engine, drivetrain, and other technologies into this section on lifetime costs. This NPV analysis involves an assessment of an initial consumer cost for the climate change reduction technologies and the potential net lifetime benefits in the future that result from the initial investment. If the sum of net future benefits outweighs the initial technology cost within the lifetime of the technology, the investment in the new technology is sound. The first year in which the net future benefits exceed the initial cost of the technology is called the break-even, or payback, period. The total initial cost, including the manufacturing cost plus the 40% mark-up for profit, and overhead – to consumers is K_0.

$$NPV_0 = -K_0$$

Future vehicle operator benefits and costs due to the new technology are discounted by the discount rate, or time value of money, *d,* to correct for the difference in the value of money in hand today versus money in the future (based primarily on interest rate and inflation). The NPV of the investment one year from now (in current dollars) is calculated,

$$NPV_1 = NPV_0 + \frac{\sum(Benefits,\ year\ 1) - \sum(Costs,\ year\ 1)}{(1+d)^1}$$

Or, more generally in any year *x*,

$$NPV_x = NPV_{x-1} + \frac{\sum(Benefits,\ year\ x) - \sum(Costs,\ year\ x)}{(1+d)^x}$$

Following historical trends, the analysis uses a real discount rate, or time value of money, of 5%. These values for the discount rate are based on ten-year averages of automobile interest rate and the general inflation rate (See Appendix D, Part 1). The benefits of the new technologies are the reductions in operational costs of vehicle travel over the lifetime of the vehicle. In this case, many of the climate change reduction technologies have indirect private cost benefits due to the reduction of the costs associated with vehicle fuel usage. The effects of the new engine and drivetrain technology systems on the lifetime vehicle maintenance costs are currently being investigated. For example, technologies that involve a reduction of the number of moving parts, like a camless valve actuation system, are expected to reduce lifetime maintenance costs. Similarly, lower leakage rate air conditioning systems should reduce maintenance costs. Without comprehensive data on these effects, these maintenance cost are excluded here. In the case of refrigerant emissions, the potential reduction in maintenance costs due to low-leak systems is being evaluated and is expected to be discussed further in May staff report.

The costs of the different fuels that are considered in this report were provided by the California Energy Commission (CEC). For gasoline and diesel fuels, the prices are inflation adjusted from the values in the CEC's *Integrated Energy Policy Report* (CEC, 2004). For gasoline the price is $1.74 per gallon, and the diesel price is $1.73 per gallon (in 2004 dollars). These values are roughly consistent with the 3-yr historical California fuel prices.

The costs and lifetime benefits for the technology packages were evaluated over the vehicle lifetime, using the same vehicle use parameters as Section III (from Appendix B). Further discussion of the NPV analysis and the variables applied to it can be found in Appendix D and an analysis of the sensitivity of the results to changes in these assumptions will be presented in the final ARB staff report.

A. ENGINE, DRIVETRAIN, AND HYBRID-ELECTRIC VEHICLE TECHNOLOGIES

Estimations for the incremental cost to the manufacturer and the retail price equivalent to consumers for each of the technologies considered were described previously in Section III. These costs are the initial capital cost to consumers for the net present value analysis.

Figures III-1 through III-5 show the results of the net present value assessment of each technology package for the five different vehicle types. These figures plot the packages' incremental cost versus the resulting greenhouse gas reduction from the technology packages. The diagonal lines in the figures show, for given economic assumptions, the break-even cut-off for the technologies, such that the furthest right-most point that is under the "break-even" line is the maximum potential cost-effective reduction of greenhouse gases for that vehicle class. The data points have been shaped differently to reflect their expected market readiness. Near-term technology packages are diamonds, mid-term are triangles, and long-term are "X"s.

For the small cars (See Figure IV-1), the maximum cost-effective near-term technology package of those studied was one with a turbocharged stoichiometric gasoline direct injection (GDI-S) engine with dual cam phasing (DCP) and an automated manual transmission (AMT), and various other technology improvements. This package yielded a 22% CO_2 emission reduction for an additional cost of about $600 from the 2009 small car baseline. The package, under the economic assumptions described above, resulted in a 4-yr break-even period for vehicle consumers, and yielded a $1,100 lifetime net present value (2004$), including the initial cost of the technologies and the discounted benefits over the 16-yr lifetime of the vehicle. The highest cost-effective reduction mid-term technology scenario for small cars included homogeneous combustion compression ignition (HCCI) technology and offered a 26% CO_2 emission with an 11-yr payback to consumers. The longer-term (beyond 2009) technologies, like advanced and moderate hybrid-electric, also resulted in higher potential cost-effective CO_2 reductions.

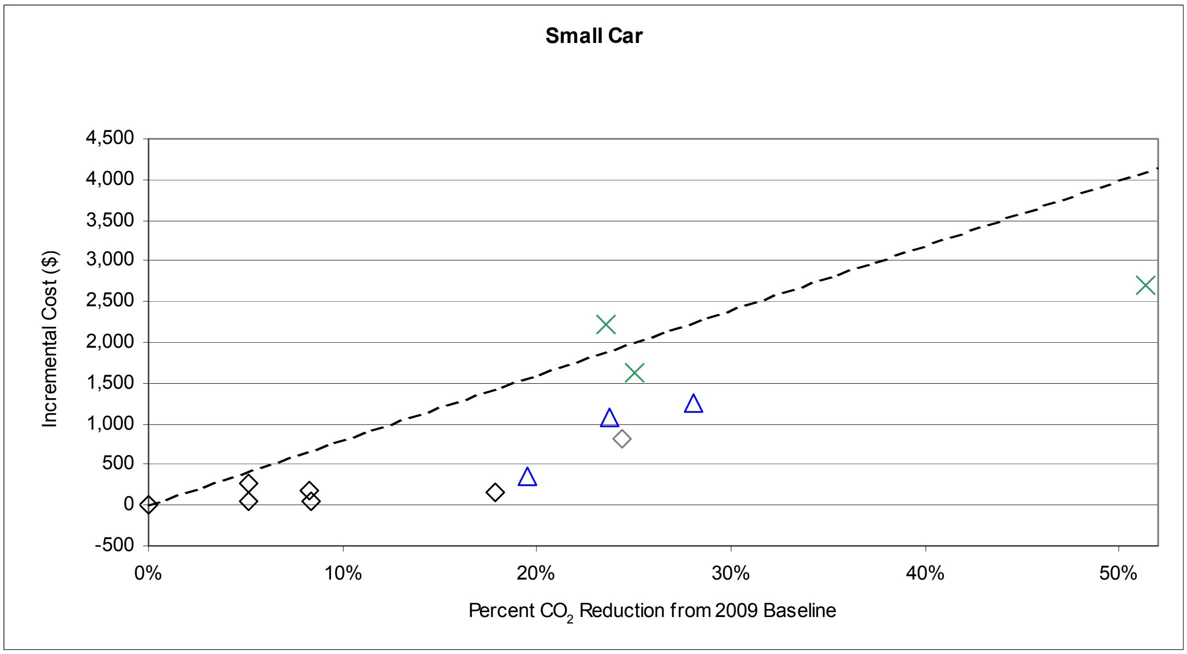


Figure IV-1. Cost and CO_2 Reduction for Technology Packages on 2009 Baseline Small Cars

For large cars (See Figure IV-2), the maximum cost-effective mid-term technology package in the analysis was the turbocharged stoichiometric gasoline direct injection (GDI-S) engine with dual cam phasing (DCP), and a 6-speed automatic transmission (A6). This package yielded a 20% reduction in exhaust CO_2 emissions for an increased initial cost of about $750 from the 2009 large car baseline. The package was roughly the same cost as the large car 2009 baseline and yielded a $2,000 lifetime net present value (2004$), over the 16-yr lifetime of the vehicle. In the mid-term, a very similar package that also included a 42-volt integrated starter-generator resulted in a 29% reduction in CO_2 emissions with a 3-yr payback. The longer-term advanced hybrid-electric vehicle technology resulted in a higher potential cost-effective CO_2 emission reduction of approximately 50%.

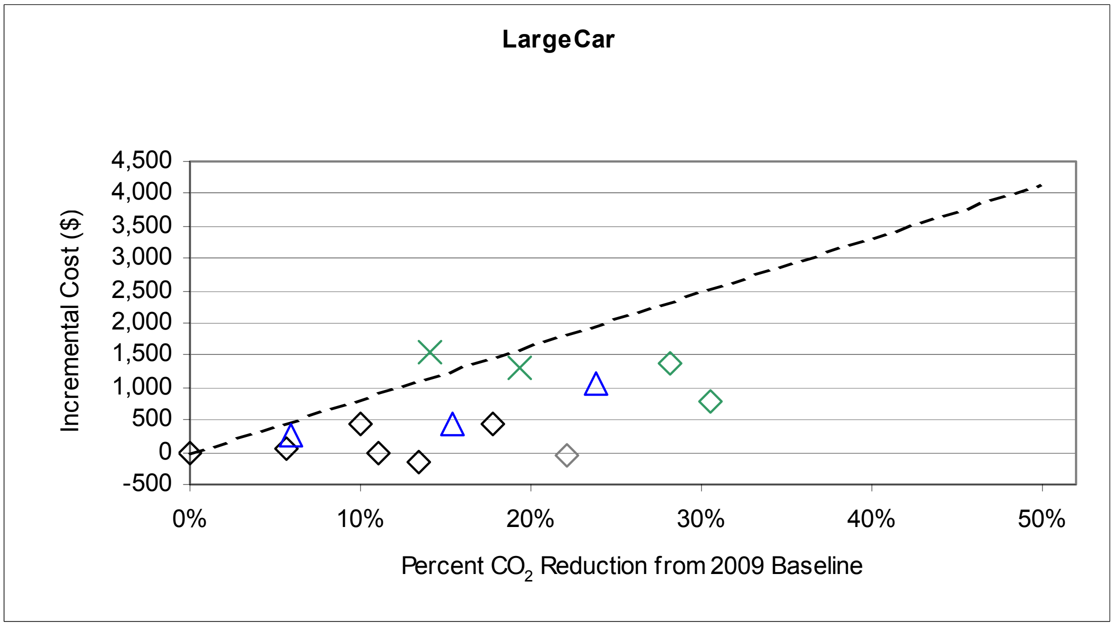


Figure IV-2. Cost and CO_2 Reduction for Technology Packages on 2009 Baseline Large Cars

For the minivan (See Figure IV-3), the maximum cost-effective near-term technology package in the analysis was determined to be the stoichiometric gasoline direct injection (GDI-S) engine with coupled cam phasing (CCP), and an automated manual transmission (AMT). This package yielded a 17% reduction in exhaust CO_2 emissions for an increased initial cost of about $1,000 from the 2009 large car baseline. The package resulted in a 5-yr break-even period for vehicle consumers, and yielded a $1,800 lifetime net present value (2004$). A similar package that also included cylinder deactivation (DeAct) and a 42-volt integrated starter-generator (ISG) resulted in a 20% CO_2 reduction, $1,200 initial cost, and 10-yr payback period. The longer-term (beyond 2009) technologies, like advanced and moderate hybrid-electrics, resulted in higher potential cost-effective CO_2 reductions.

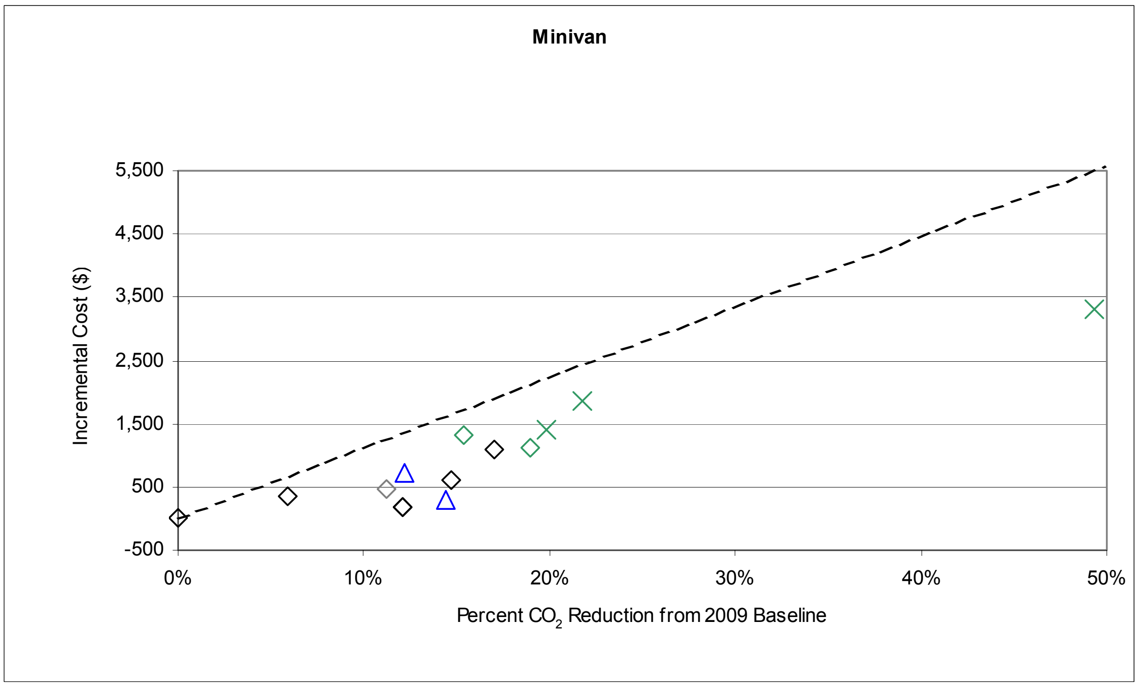


Figure IV-3. Cost and CO_2 Reduction for Technology Packages on 2009 Baseline Minivans

For the small truck (See Figure IV-4), there were three scenarios that resulted in cost-effective CO_2 reductions of about 20%. The near-term scenario with turbocharging, stoichiometric gasoline direct-injection, dual cam phasing (DCP), and an automated manual transmission (AMT), yielded a cost-effective 19% reduction in exhaust CO_2 emissions. The stoichiometric gasoline direct-injection engine with electrohydraulic camless valve actuation and an automated manual transmission (AMT) offered a 22% CO_2 emission reduction with a 3-yr payback to consumers. Another scenario with cylinder deactivation (DeAct), discrete variable valve lift (DVVL), coupled cam phasing (CCP), a 42-volt integrated starter-generator (ISG), and a 6-speed automatic transmission (A6), yielded a 20% reduction in exhaust CO_2 emissions for an increased initial cost of about $1,000 from the 2009 large car baseline. The package resulted in a 6-yr break-even period for vehicle consumers, and yielded a $1,300 lifetime net present value (2004$). The longer-term (beyond 2009) technologies, like advanced and moderate hybrid-electric vehicles, resulted in higher potential cost-effective CO_2 reductions.

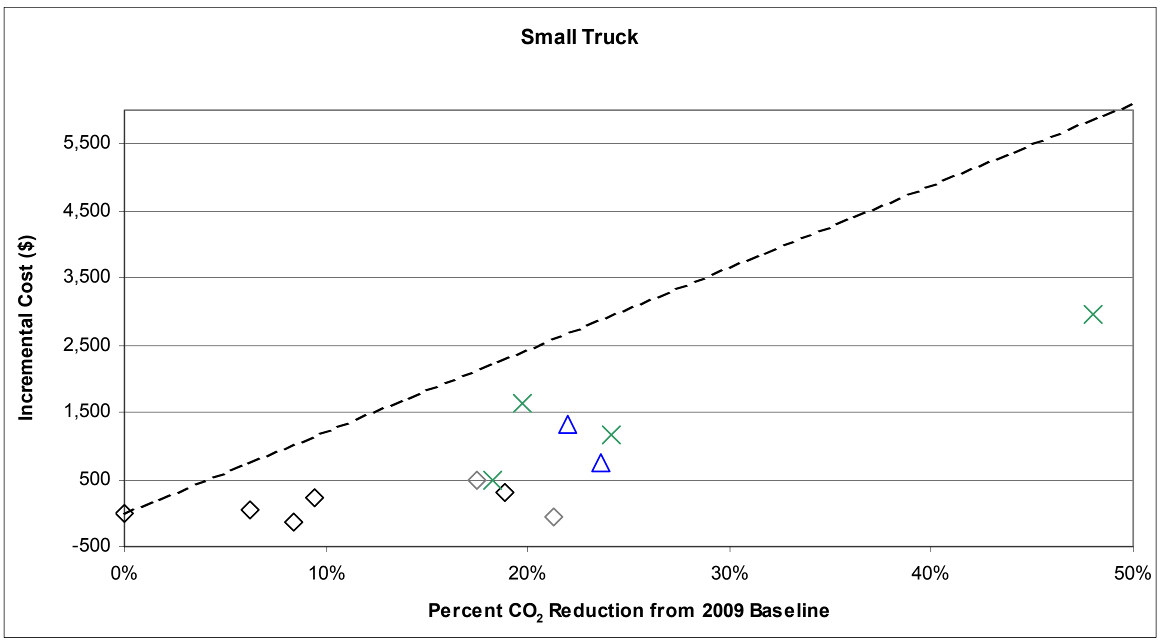


Figure IV-4. Cost and CO_2 Reduction for Technology Packages on 2009 Baseline Small Trucks

For the large trucks (See Figure IV-5), the maximum cost-effective scenarios included near- and mid-term CO_2 emission reduction packages involved cylinder deactivation, coupled cam phasing, and variable valve lift. The near-term version, which included an automated manual transmission (AMT), had a 16% CO_2 emission reduction relative to the 2009 baseline vehicle with a 2-yr break-even period for the vehicle operator. The more advanced version of this package also included a 42-volt integrated starter-generator (ISG) and had a 20% CO_2 reduction with a $1,600 incremental cost from the 2009 large car baseline. The package resulted in a 6-yr break-even period for vehicle consumers, and yielded a net $1,300 lifetime net present value benefit. The longer-term (beyond 2009) technologies, like lean-burn gasoline direct injection engines and advanced hybrid-electric, resulted in higher potential cost-effective CO_2 emissions.

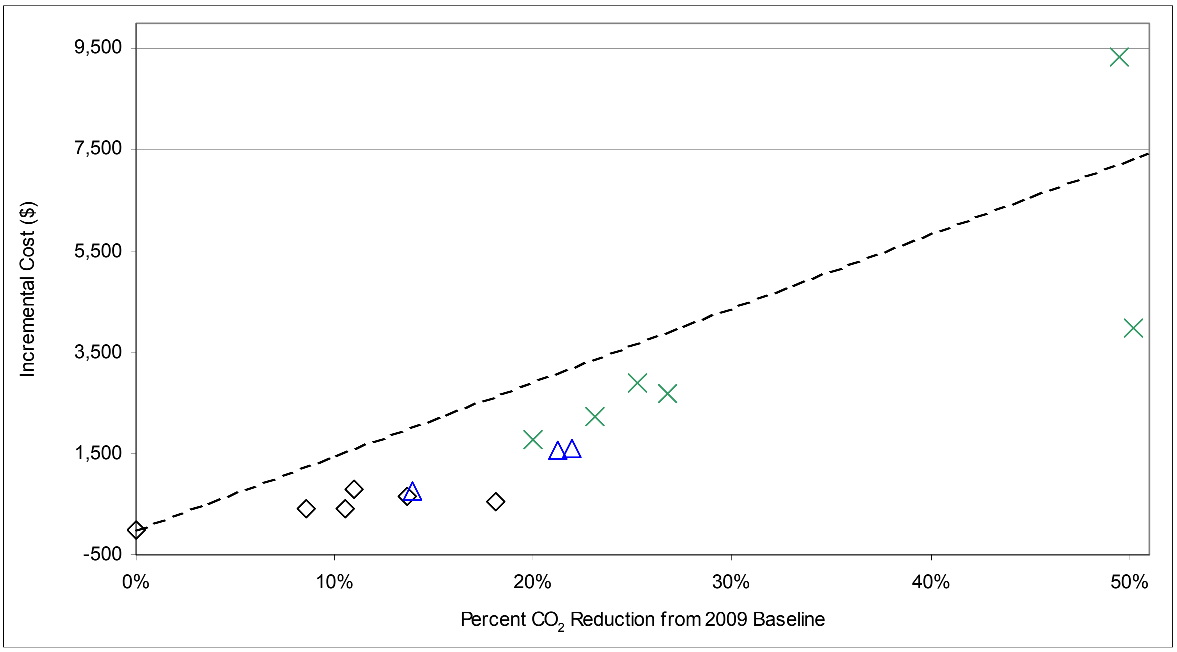


Figure IV-5. Cost and CO_2 Reduction for Technology Packages on 2009 Baseline Large Trucks

B. ALTERNATIVE FUEL VEHICLES

The potential cost-effectiveness analysis of deploying alternative fuel vehicles to reduce greenhouse gases is ongoing. In this section alternative fuel vehicles are compared with their conventional baseline gasoline counterparts. This analysis of alternative fuel vehicles is similar to that of the net present value analysis of the engine and drivetrain technologies above. However, for this analysis comprehensive data on how alternative fuel technologies differ among different vehicle types (e.g. small cars and large trucks) were not available. Our baseline conventional vehicle is the California-specific sales weighting of the 2009 baseline small and large cars (i.e. trucks, minvans, etc. are excluded). Incremental retail costs associated with equipping the vehicles to operate on alternative fuels were researched by the ARB staff. These costs are shown in Table IV-6. Applying the same vehicle use characteristics (VMT/yr, vehicle lifetime) as above, the net present value of the vehicle alternatives was evaluated.

Our preliminary findings suggest that, with the exception of the plug-in hybrid-electric vehicle, none of the vehicles studied here would likely be economical to vehicle operators. Each vehicle that costs were available for, excluding the plug-in hybrid, had negative lifetime net present values in the thousands of dollars.

Table IV-6. Incremental Cost and Cost Effectiveness of Alternative Fuel Vehicles

Vehicle-fuel systems	Distance per fuel usage (miles/fuel unit)	Fuel usage (fuel unit/mi)	Fuel unit	Fuel cost ($/fuel unit)	Cost increment from 2009 baseline	Lifetime (16-yr) Net Present Value (2004$)	Payback period
Conventional vehicles	27.1	0.037	GGE	1.74	0	0	0
Compressed natural gas (CNG)	20	0.050	GGE	1.63	3600	(6,039)	>16
Liquified natural gas (LNG)	-	-	DGE	1.96	-	-	-
Liquid propane gas (LPG)	15.8	0.063	LPG gal	1.31	700	(3,342)	>16
Plug-in Hybrid	2	0.500	$/kWh	0.11	-	-	-
	45	0.022	GGE	1.74	-	-	-
					5700	691	14
Ethanol (E85)	19	0.053	e85 gal	1.55	0	(2,412)	0
Hydrogen Combustion	-	-	GGE	4.22	-	-	-

[1] *from CEC, 2004* [2] *Unnasch, 2004*

V. CONCLUSIONS

Identified in this analysis are a large number of technologies that reduce greenhouse gas emissions. The technologies range from low friction oils to advanced hybrid electric drive trains. Many of the technologies, especially those involving the engine valve train and transmission, are used on some cars now, and could be in near universal use in the 2009 timeframe. Other technologies are still undergoing development, and can be expected to be available for widespread use after 2010. These include advanced valve trains and advanced hybrid electric drives.

Logical combinations of these technologies have been modeled to determine the potential to reduce greenhouse gas emissions from different size vehicles. The cost of the technology packages has also been determined, as has their impact on operating costs. Reductions in CO_2-equivalent emissions, compared to emissions of 2009 models in the absence of government regulation, vary widely, from a few percent to over 45 percent. In general the higher percentage reductions involve technologies that may not be widely available in 2009, but are expected to be available sometime after 2010.

Several technologies stood out as providing significant reductions in emissions at favorable costs. These include discrete variable valve lift, dual cam phasing, turbocharging with engine downsizing, automated manual transmissions, and camless valve actuation. Packages containing these and other technologies such as improved air conditioning compressors provided substantial emission reductions at prices that ranged from a saving to several hundreds of dollars. Nearly all technology combinations modeled provided reductions in lifetime operating costs that exceeded the retail price of the technology.

VI. REFERENCES

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VII. APPENDICES

APPENDIX A: HYBRID DRIVE VEHICLES AND CLIMATE CHANGE

1. Hybrid Electric Vehicles

Most automakers today have hybrid-electric powerplants under development or in production. There are also investigations into the use of hydraulic-hybrid vehicles that use hydraulic motors and accumulators as a supplementary power source. The US EPA is currently funding research into hydraulic hybrids and is particularly interested in their application in medium and heavy duty vehicles.

Recent breakthroughs in the technologies necessary for powerplant hybridization with electric motors have made electric power the most popular means to supplement conventional engines in light and medium duty vehicles. These breakthroughs include availability of affordable microprocessor controls to manage the complexity of hybrid power systems and optimize performance, very high specific power motors, the availability of affordable power-switching electronics able to control high currents for maintenance-free brushless motors and for use in high power DC-DC power converters, and high specific power maintenance-free NiMH batteries with lifetimes that can meet or exceed the lifetime of the rest of the vehicle if cycled within narrow operating limits.

Hybrid-Electric Benefits

Reductions in climate change emissions from hybrid-electrics result from accumulation and re-use of energy normally lost in braking (regenerative braking), engine shut down while the vehicle is stationary (idle-stop), downsizing the engine or enabling the incorporation of alternative engine technologies, and supplementary torque and energy storage that allow the engine to operate more frequently at optimal operating points. Integral or electronic CVT function allows further restriction of the engine to even more optimal operating points, similar to improvements from adding gear ratios or CVTs to non-hybrids.

The benefits of electric hybridization are not limited to reductions in climate change emissions. This makes it a challenge to assess the costs and benefits of hybrid-electrics because it is difficult to allocate the costs across the array of benefits. The features and benefits of hybridization can vary considerably depending on what features are emphasized in a particular design. These potential hybrid-electric benefits include reduction in climate change emissions, improved acceleration performance characteristics (both additional tractive torque and faster availability of this supplementary torque), simplification and/or improvements in transmission functions, and elimination (replacement) of the starter motor. Hybrids can reduce real-life emissions of criteria pollutants relative to conventional engines due to better management of transient behavior. Hybrids also offer the potential to replace the mechanical flywheel function with electric pulse torque damping, and replace the conventional alternator with a higher power and more efficient brushless system. With the addition of an inverter, this also allows automakers to offer a portable, quiet, auto-start, low-emission auxiliary power unit. Finally, the availability of high-voltage power enables other on-vehicle applications such as electric turbocharging, power steering, camless valve actuation, and windshield defrosting, and driving in all-electric mode. This in turn provides redundancy—the ability to drive to a repair facility with an inoperative engine.

Although the application of hybrid-electric technology will most likely reduce the climate change emissions of vehicles that are so equipped, this benefit may not be the primary intent of the automotive engineers when developing a particular vehicle. Hybridization can enable the application of otherwise unrelated engine technologies, in particular, technologies that sacrifice engine specific torque output or transient torque performance. These may be augmented by the supplemental torque and fast response of the hybrid motor. Examples include Atkinson cycle designs, some displacement-on-demand schemes, and the hydrogen ICE. The use of hybrid electric drive and electric turbocharging technology in combination with hydrogen as a combustion fuel may enable hybrid electric hydrogen ICE vehicles to rival near-term fuel cell vehicles in terms of reduction in climate change emissions. Hybrid hydrogen ICEs provide near-zero tailpipe emissions and may create an affordable "bridge" to the hydrogen economy.

All of these considerations and potential synergies make it challenging to assess the ultimate potential of hybrid-electric vehicles. In order to thoroughly model and predict these potential improvements, a great deal of system design and optimization work would be required which would push this analysis well beyond the scope of research and into the realm of actual vehicle design. Additionally, there are very few entities in the world that have the capability to perform this work, and they are in the business of making cars and are unlikely to want to reveal the necessary proprietary information. There are few non-automotive entities that are capable of reverse-engineering the existing production hybrids in order to understand how they work at a sufficient level of detail. For these reasons, staff has instead chosen to focus on the features, performance and climate change improvements of the first few hybrid electric vehicles offered for sale, with the caveat that these results are not representative of the ultimate climate change reduction performance of hybrid electric technology. Development efforts are still underway and automakers have publicly announced that further gains from the use of hybrid electric technology should be expected.

The two production hybrids summarized below are cited as minimum examples of the climate change emissions reduction performance attainable by hybrids that are optimized for this purpose as opposed to acceleration performance improvement.

Table II-10: Comparison of HEVs vs Conventional Vehicles

Make/ Model	CO_2 g/mile	% Reduction 2004
"Strong" HEV		
2004 Prius	159	54%
Average Midsize and Compact	343	
"Mild" HEV		
2004 Civic HEV	186	29%
2004 Civic	262	

Hybrid-Electric Vehicle Cost

Many of the challenges with predicting the ultimate climate change emission reduction of hybrid electric vehicles also make it difficult to estimate the costs necessary to implement this technology. Hybrids are a relatively immature technology that are still experiencing substantial design upgrades from one product design cycle to the next.

Toyota does not presently offer a mid-size automobile of exactly the same size and trim level as the hybrid-electric Prius. Toyota engineers have stated, however, that the cost difference between the Prius and a comparable non-hybrid vehicle would be approximately $1,500. Honda's Civic "mild" hybrid MSRP is currently $19,650, while its Civic EX MT coupe MSRP is $16,860. This is not an exact comparison because the Civic EX lacks some of the hybrid's trim features. Nevertheless the MSRP difference of $2,790 provides another data point regarding the current cost of hybrid technologies at the consumer level.

Table II-11 below summarizes the ARB staff assessment of projected 2009 cost for hybrid electric vehicles.

Table II-11. ARB Staff Assessment of Hybrid Costs

Vehicle class (ex.vehicle)	Hybrid type	Manufactured Cost (2004$)	Retail Price Equivalent ($)
Compact (~Civic)	Mild	1,258	1,761
	Full	1,972	2,761
Small Car (~Cavalier)	Mild	1,384	1,937
	Full	2,155	3,017
Mid Size (~Taurus)	Mild	1,514	2,119
	Full	2,502	3,503
Pickup (~Silverado)	Mild	1,672	2,340
	Full	2,922	4,091
Minivan (~Caravan)	Mild	1,548	2,167
	Full	2,593	3,631
Std SUV	Mild	1,480	2,071

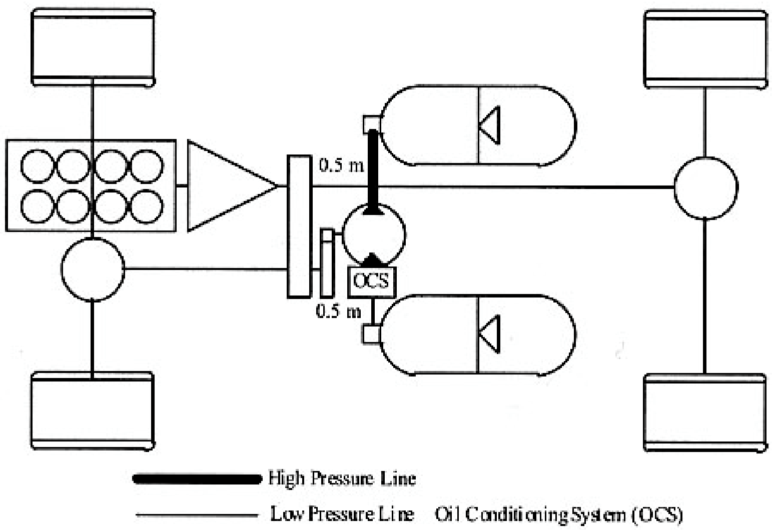
It is important to keep in mind that the allocation of hybrid electric component costs across the potential consumer benefits is challenging, and will become more so as higher performance models such as the Lexus 400h or APU models such as the Chevrolet and Dodge pickups begin sales in the next 2 years. Both of the APU systems are supplied by Continental-Teves, with the GM system providing 2.4 kW, and the Daimler producing 5 kW of off-board AC power. It would make sense to allocate some of the additional cost of this hybrid technology to the APU feature, but a comparison will be difficult

In the case of performance hybrids such as the Lexus 400h, Toyota is conservatively claiming that the hybrid V6 will have the performance of a V8 model. In fact, its off-the-line acceleration and passing performance will probably exceed the performance of the V8, and even its worst case attributes will exceed or match V8 performance. When it comes to equivalent non-hybrid performance options, customers have shown a willingness to pay a great deal of money for these sorts of gains. As with the APU option, it will be challenging to ascertain what fraction of the cost to allocate to improved acceleration performance, and what amount to allocate to reduction of climate change emissions.

Hydraulic Hybrid Vehicle

Mild Hydraulic Hybrid Drivetrain (with both engine-on (where the engine is always on unless operator shuts it off) and engine-off (with engine on and engine off cycling) strategies))

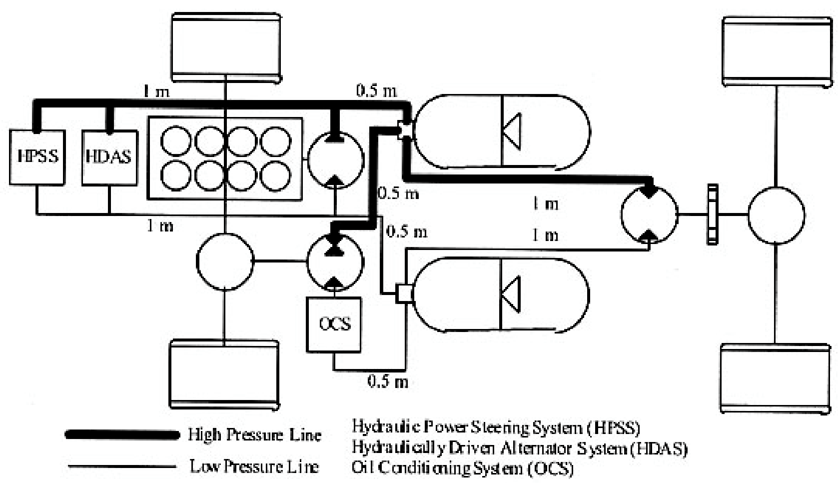
The federal EPA has been developing a mild hydraulic hybrid vehicle based on a 1999 Ford Taurus that has both a conventional vehicle powertrain and a hydraulic secondary energy storage system. The hydraulic system captures and stores a large fraction of



the energy normally wasted in vehicle braking to help propel the vehicle during the next acceleration. The primary components of the hydraulic system are two hydraulic accumulator vessels (a high-pressure accumulator capable of storing hydraulic fluid compressing inert nitrogen gas and a low-pressure accumulator) and a hydraulic pump/motor unit. When operating as a pump, the pump/motor "pressurizes" the high-pressure accumulator by pumping in greater volumes of hydraulic fluid during braking. When operating as a motor, it utilizes the high-pressure hydraulic fluid to supply additional torque to the driveshaft during acceleration. EPA tests indicate a potential reduction in CO_2 emissions from their gasoline prototype of about 9% (using an engine-on strategy) and 15% (using an engine-off strategy) compared to a non-hybrid version of their test vehicle.

Full Hydraulic Hybrid Drivetrain (with both engine-on and engine-off strategies)

Full hydraulic hybrid vehicles are designed to maximize the benefits of a hydraulic powertrain. There are a vast number of unique designs and control systems that could be used in a full hydraulic hybrid vehicle, which can provide the following benefits: (1) the potential capture and re-use up to 80% of braking energy, (2) much greater use of engine-off strategies and maximizes the operation of the engine at or near its peak efficiency and (3) the possibility of downsizing the engine (assumed in the EPA study). In the full hydraulic hybrid design evaluated by EPA, based on a 1999 Ford Expedition, the automatic transmission is eliminated and replaced with a hydraulic hybrid drivetrain. The engine is downsized and coupled to a hydraulic pump/motor. This pump/motor can operate as a pump to supply hydraulic power to the drive motors and/or to fill the high-pressure accumulator as needed and can also be used to start the engine when operated as a motor.



A second hydraulic pump/motor is integrated into the front differential. This pump/motor is used to accelerate the vehicle, when operated as a motor, and it provides regenerative braking when operated as a pump.

Another motor is integrated into the rear drive assembly, which also includes a two-speed gearbox and a differential. This motor is used for vehicle acceleration but not for braking.

EPA tests indicate a potential reduction in CO_2 emissions from their gasoline prototype of about 18% (using an engine-on strategy) and 32% (using an engine-off strategy) compared to a non-hybrid version of their test vehicle.

APPENDIX B: AVERAGE VEHICLE TRAVEL

From EMFAC2002, Version 2.2 (Apr03), statewide, MY2010 from 2010 through 2040. Gasoline vehicle mileage accrual obtained from EMFAC weight output file. Gasoline vehicle survival rates from EMFAC model code, derived from DMV data.

Table B-1. Median Vehicle Use

Year	Vehicle age	Light-Duty Autos - Gasoline			Light-Duty Trucks (LDT1)			Light-Duty Trucks (LDT2)		
		Annual VMT (mi/yr)	Survival Rates	Cumulative annual VMT (mi/yr/veh)	Annual VMT (mi/yr)	Survival Rates	Cumulative annual VMT (mi/yr/veh)	Annual VMT (mi/yr)	Survival Rates	Cumulative annual VMT (mi/yr/veh)
2010	1	16,071	1.000	16,071	17,568	1.000	17,568	17,009	1.000	17,009
2011	2	15,530	0.972	31,601	16,184	0.979	33,752	15,745	0.980	32,754
2012	3	15,006	0.957	46,607	15,205	0.965	48,957	14,847	0.967	47,601
2013	4	14,503	0.947	61,110	14,429	0.949	63,386	14,135	0.954	61,736
2014	5	14,015	0.931	75,125	13,782	0.933	77,168	13,538	0.943	75,274
2015	6	13,545	0.915	88,670	13,224	0.916	90,392	13,023	0.929	88,297
2016	7	13,089	0.894	101,759	12,731	0.897	103,123	12,567	0.915	100,864
2017	8	12,649	0.869	114,408	12,289	0.875	115,412	12,158	0.895	113,022
2018	9	12,224	0.837	126,632	11,890	0.848	127,302	11,787	0.873	124,809
2019	10	11,815	0.803	138,447	11,526	0.818	138,828	11,448	0.845	136,257
2020	11	11,418	0.763	149,865	11,190	0.784	150,018	11,134	0.815	147,391
2021	12	11,036	0.720	160,901	10,880	0.751	160,898	10,845	0.781	158,236
2022	13	10,667	0.674	171,568	10,591	0.708	171,489	10,574	0.741	168,810
2023	14	10,310	0.619	181,878	10,320	0.667	181,809	10,321	0.700	179,131
2024	15	9,966	0.566	191,844	10,066	0.629	191,875	10,082	0.663	189,213
2025	16	9,633	0.506	201,477	9,826	0.582	201,701	9,857	0.619	199,070
2026	17	9,312	0.443	210,789	9,602	0.541	211,303	9,647	0.577	208,717
2027	18	9,003	0.382	219,792	9,391	0.493	220,694	9,448	0.527	218,165
2028	19	8,705	0.333	228,497	9,190	0.450	229,884	9,258	0.484	227,423
2029	20	8,415	0.291	236,912	9,000	0.413	238,884	9,078	0.447	236,501
2030	21	8,137	0.255	245,049	8,818	0.377	247,702	8,907	0.408	245,408
Median Lifetime Vehicle Mileage		202,329			219,234			223,969		
Median Vehicle Age		16			18			19		

APPENDIX C: MOBILE AIR CONDITIONING SYSTEM ASSESSMENT

The following Appendices can be found at http://www.arb.ca.gov/cc/cc.htm

Appendix C.1, Mobile Air Conditioning System Technology Assessment, California Air Resources Board, Research Division

Appendix C.2, Air Conditioning Thermodynamics, California Air Resources Board, Research Division

Appendix C.3, HFC-134a Emissions from Current Light- and Medium-Duty Vehicles, California Air Resources Board, Research Division

Appendix C.4, Mobile Air Conditioning Systems - Indirect Emissions, California Air Resources Board

APPENDIX D: NET PRESENT VALUE ANALYSIS ASSUMPTIONS

1. Discount Rate

In Table D-1, the estimated discount rate is derived from historical data for the past ten years on nominal car loan interest rates and the inflation rate. Annual nominal interest rates were taken from the Federal Reserve Statistical Release (FSRS, 2004), and inflation rates are from consumer price index data that was published by the U.S. Department of Labor's Bureau of Labor Statistics (2004). The difference between the nominal interest rate on car loans and the inflation rate is the real interest rate on car loans, which approximates the real discount rate comparing economic alternatives with respect to automobiles. Utilizing these data, this assessment took a 5% discount rate for its baseline calculations. We applied 3% and 7% rates in the sensitivity analysis to recognize the variability of the rate.

Table D-1. Determination of Real Interest Rate

Year	Nominal interest rate on car loan[1]	Inflation rate[2]	Real interest rate on car loan
1994	9.79	2.67	7.12
1995	11.19	2.54	8.65
1996	9.84	3.32	6.52
1997	7.13	1.70	5.43
1998	6.30	1.61	4.69
1999	6.66	2.68	3.98
2000	6.61	3.39	3.22
2001	5.64	1.55	4.09
2002	4.29	2.38	1.91
2003	3.4	1.88	1.52
Average	**7.1**	**2.4**	**4.7**

[1] FRSR, 2004; [2] Bureau of Labor Statistics, 2004

2. Derivation of Break-Even Lines

This section derives the diagonal "break-even" lines for Figures IV-1 through IV-5 in the "Engine, Drivetrain, and Hybrid-Electric Vehicle Technologies" section of the cost assessment. These lines represent the point at which, for given vehicle use and economic assumptions, the incremental technology retail cost and carbon dioxide percentage reduction leads to a break-even investment for the vehicle user. Points above this line represent technology scenarios that have payback periods greater than the vehicle lifetime. Points below this line represent payback periods less than the vehicle lifetime, and are, therefore, according to the language of AB 1493, "cost effective." For this derivation, we assume a linear relationship between carbon dioxide emissions (in grams per mile) and fuel usage (in gallons of fuel per mile), such that the percentage reduction in one is equivalent to a percentage reduction in the other.

Following a standard net present value (NPV) framework, the present value of the initial capital cost to the user or purchaser of a new technology in year 0 is K_0

$$NPV_0 = -K_0$$

And the net present value one year from the initial investment includes the net sum of the benefits and costs accrued during that year due to the new technology investment, discounted by the discount rate, or time value of money, *d*.

$$NPV_1 = NPV_0 + \frac{\sum(Benefits,\ year\ 1) - \sum(Costs,\ year\ 1)}{(1+d)^1}$$

Or generally for year x:

$$NPV_x = NPV_{x-1} + \frac{\sum(Benefits,\ year\ x) - \sum(Costs,\ year\ x)}{(1+d)^x}$$

Assuming no additional operating cost with the new technology:

$$NPV_x = NPV_{x-1} + \frac{\sum(Benefits,\ year\ x)}{(1+d)^x}$$

Recognizing the potential reduction in fuel usage due to the application of feasible, cost-effective climate change reduction technologies, variables for potential fuel savings are inputted as the benefits:

$$NPV_x = -K_0 + \sum_{x=1}^{x=lifetime} \begin{pmatrix} Fuel\ Savings \\ \$/mile \end{pmatrix}_x \frac{1}{(1+d)^x} (mi/yr)_x$$

$$NPV_x = -K_0 + \sum_{x=1}^{x=lifetime} \begin{pmatrix} Fuel \\ price \end{pmatrix} \begin{pmatrix} Percent \\ fuel\ usage \\ reduction \end{pmatrix} \begin{pmatrix} Fuel \\ usage \\ rate \end{pmatrix} \frac{1}{(1+d)^x} (mi/yr)_x$$

And because the percentage fuel usage reduction is equivalent to the percentage carbon dioxide emission reduction for the technologies of Section II.A

$$NPV_x = -K_0 + \sum_{x=1}^{x=lifetime} \begin{pmatrix} Fuel \\ price \end{pmatrix} \begin{pmatrix} Percent \\ CO_2 \\ reduction \end{pmatrix} \begin{pmatrix} Fuel \\ usage \\ rate \end{pmatrix} \frac{1}{(1+d)^x} (mi/yr)_x$$

Assuming the real price of fuel, and vehicle fuel usage per mile, and the percentage fuel usage reduction are constant over the vehicle lifetime

$$NPV_x = -K_0 + \begin{pmatrix} Fuel \\ price \end{pmatrix} \begin{pmatrix} Percent \\ CO_2 \\ reduction \end{pmatrix} \begin{pmatrix} Fuel \\ usage \\ rate \end{pmatrix} \sum_{x=1}^{x=lifetime} \frac{1}{(1+d)^x} (mi/yr)_x$$

For break-even, solve for NPV = 0 at vehicle lifetime to determine the incremental cost that corresponds with each CO_2 reduction.

$$0 = -K_0 + \begin{pmatrix} Fuel \\ price \end{pmatrix} \begin{pmatrix} \%\ CO_2 \\ reduction \end{pmatrix} \begin{pmatrix} Fuel \\ usage \\ rate \end{pmatrix} \sum_{x=1}^{x=lifetime} \frac{1}{(1+d)^x} (mi/yr)_x$$

$$K_0 = \begin{pmatrix} Fuel \\ price \end{pmatrix} \begin{pmatrix} \%\ CO_2 \\ reduction \end{pmatrix} \begin{pmatrix} Fuel \\ usage \\ rate \end{pmatrix} \sum_{x=1}^{x=lifetime} \frac{1}{(1+d)^x} (mi/yr)_x$$

Solving for initial incremental cost per percent CO_2 reduction, and inputting the appropriate vehicle variables, defines the slope of the lines in Figure IV-1 through IV-5:

$$\frac{K_0}{\begin{pmatrix} \%\ CO_2 \\ reduction \end{pmatrix}} = \begin{pmatrix} Fuel \\ price \end{pmatrix} \begin{pmatrix} Fuel \\ usage \\ rate \end{pmatrix} \sum_{x=1}^{x=lifetime} \frac{1}{(1+d)^x} (mi/yr)_x$$