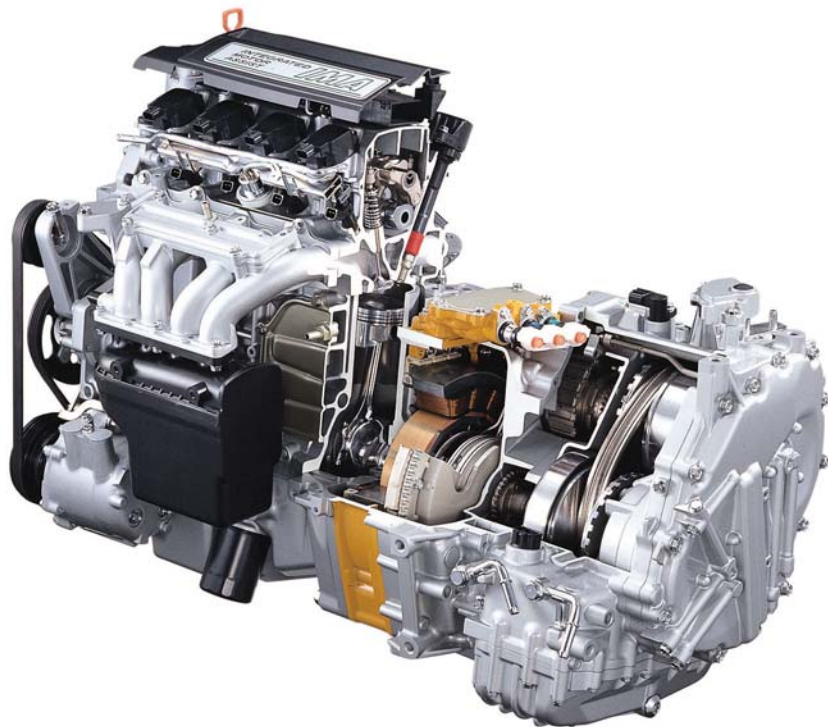


# Exploring Greenhouse Gas Reduction Options for Automobiles



A REPORT ON THE  
INTERNATIONAL VEHICLE TECHNOLOGY SYMPOSIUM



**ENVIRONMENTAL DEFENSE**

finding the ways that work



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INTERNATIONAL VEHICLE TECHNOLOGY SYMPOSIUM

AUTHOR

**Sebastian Vicuna**

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Cutaway view of the 2003 Honda Civic Hybrid engine.

Our mission

Environmental Defense is dedicated to protecting the environmental rights of all people, including the right to clean air, clean water, healthy food and flourishing ecosystems. Guided by science, we work to create practical solutions that win lasting political, economic and social support because they are nonpartisan, cost-effective and fair.

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## **Editorial Note**

This report is based on a review of the presentations made at the International Vehicle Technology Symposium held in Sacramento by the California Air Resources Board on March 11–13, 2003. It was written by Sebastian Vicuna, an engineering intern at Environmental Defense, under the guidance of Environmental Defense staff members John DeCicco, Kate Larsen and Nancy Ryan. The author reviewed both the video record of the symposium and the presentation materials provided by participants.

This report does not attempt to provide background on "how cars work" or other elements of automotive engineering. Therefore, some readers may wish to supplement it with introductory material on automotive technology; several references are given in the notes. Interpretation of the information, including further assessment of the applicability, benefits and cost-effectiveness of the options discussed here, is left up to the reader. The report's intent is to provide a concise record of the information presented at the symposium, which was itself intended to educate policy makers, stakeholders and interested members of the public about the technological options for reducing greenhouse gas emissions from passenger automobiles including cars and light duty trucks.

## **Disclaimer**

Although the International Vehicle Technology Symposium was sponsored by the California Air Resources Board, this summary of the proceedings was prepared solely by Environmental Defense. The descriptions contained in the summary are those of the author and editors and do not in any way represent findings or conclusions of the California Air Resources Board or its staff.

The author and editors made every attempt to adhere to the information presented at the symposium. Statements, views and interpretations that readers may infer from this text represent only the product of such reporting. Environmental Defense does not necessarily endorse statements made in this report, nor do views, interpretations, or positions given in the report necessarily represent those of Environmental Defense.



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## Executive Summary

On March 11–13, 2003, the California Air Resources Board (CARB) hosted an International Vehicle Technology Symposium in Sacramento. This public event discussed current and emerging technologies for reducing greenhouse gas (GHG) emissions from personal motor vehicles including passenger cars, light-duty trucks and sport utility vehicles. Speakers at the symposium included representatives from auto manufacturers, supplier companies, academia, non-governmental organizations and consulting firms.

In California, the transportation sector contributes 48% of the state's total GHG emissions. Within transportation, light-duty vehicles produce the largest share of emissions, including 64% of carbon dioxide (CO<sub>2</sub>) and significant shares of other greenhouse gases such as methane (CH<sub>4</sub>), nitrous oxide (N<sub>2</sub>O) and hydrofluorocarbons (HFC). The symposium addressed all of the significant GHG emissions from automobiles. Experts on each of the technologies influencing emissions provided details of sources of emissions and options for reducing them, as well as technical hurdles, costs and other considerations. The result is a comprehensive picture of both the opportunities and the challenges involved in reducing GHG emissions from the automotive sector.

This report summarizes the information presented during the symposium. It generally follows the order of presentation, starting with ways to reduce automotive trace gases having global warming impacts, then addressing the range of vehicle technologies for reducing CO<sub>2</sub> emissions from fuel combustion, and finally giving results from systems analyses of vehicle improvements and GHG reductions from alternative fuels.

HFCs are a significant class of trace gas used as refrigerants in automotive air conditioners. The most common version (HFC-134a) has a global warming potential 1,300 times stronger than that of CO<sub>2</sub>. Although the release of HFC-134a is illegal, system imperfections, inadequate training and oversight, and lack of enforcement for "do it yourself" servicing, results in emissions from system leaks and when cars are serviced or scrapped. Estimated lifetime HFC emissions are equivalent to about 4% of the CO<sub>2</sub> emissions from fuel combustion for an average car. Reduction options include improving air conditioner design, restricting refrigerant sales to certified service professionals, and better servicing and disposal practices, all of which might cut emissions by half. Alternatively, HFC emissions impacts might be essentially eliminated by using new refrigerants having a much lower global warming potential. Challenges include cost and the need for further engineering development as well as potential safety or weight trade-offs associated with alternative refrigerants.

In cars, nitrous oxide (N<sub>2</sub>O) emissions largely occur as a byproduct of the catalytic converter's process of cleaning up the NO<sub>x</sub> coming out of the engine. N<sub>2</sub>O has a global warming potential of 310 and its emissions account for about 2% of the total GHG emissions from a typical light duty vehicle.

As catalytic converter technologies improve to achieve much lower NO<sub>x</sub> emissions, N<sub>2</sub>O emissions are also expected to diminish substantially.

Methane (CH<sub>4</sub>) is a byproduct of imperfect fuel combustion. As the main constituent of natural gas, it is also emitted from leaks during fueling and usage of natural gas vehicles. CH<sub>4</sub> has a global warming potential of 21 but its emissions account for only about 0.2% of the total GHG emissions from a typical gasoline light duty vehicle. Standard catalytic converters, oriented to oxidizing reactive organic gases and other non-methane hydrocarbons, are less effective at oxidizing methane. Because CH<sub>4</sub> emissions are already small for gasoline vehicles, specific efforts to reduce them further are not being pursued. However, attention is being directed to minimizing CH<sub>4</sub> emissions from natural gas vehicles.

Carbon dioxide (CO<sub>2</sub>) accounts for an estimated 94% of the overall GHG emissions from a typical light duty vehicle. On the vehicle itself, means of reducing CO<sub>2</sub> emissions fall into two broad categories: reducing the vehicle's rate of fuel consumption and changing the fuel to reduce its associated net emissions of CO<sub>2</sub> and other GHGs.

One key approach for reducing a vehicle's CO<sub>2</sub> emissions rate involves engine and transmission modifications that improve the energy efficiency of the powertrain. Many options are available but most address similar sources of powertrain inefficiency. Therefore, caution is needed when interpreting estimates for a collection of powertrain modifications. Combinations cannot be simply summed because of synergies and overlapping effects. Accounting for these interactions requires vehicle simulation analysis: Such results were presented at the symposium and are summarized below.

Examples of such modifications applicable to conventional V8 engines for U.S. SUVs and other light trucks include raising the compression ratio; improving the flow of the air and fuel mixture entering the engine's cylinders; reducing friction within the engine; and improving the efficiency of ancillary components such as the oil pump. Collectively, such design improvements along with other minor modifications might reduce direct CO<sub>2</sub> emissions by 20% in city driving and add roughly \$500 to vehicle price.

A family of technologies for improving engine efficiency falls under the heading of variable valve timing. This strategy involves the use of sophisticated electronic and mechanical components that vary exactly when and how much the valves open, thereby better controlling the engine's intake and exhaust processes. Variable valve control systems can be designed using a variety of techniques and with a range of flexibility, providing increasing degrees of optimal valve control at generally increasing cost. A fully variable system, including using the valve control mechanisms to deactivate some of the engine's cylinders at light loads, can reduce CO<sub>2</sub> emissions by as much as 20% at a manufacturing cost of roughly \$450.

Turbocharging boosts the amount of power produced by an engine of a given size. While commonly used to enhance vehicle performance, if used with a small engine so as to maintain performance, turbocharging can reduce CO<sub>2</sub> emissions. Electrically assisted turbochargers are being developed that can facilitate the use of this technique for larger, SUV-type engines, offering up to a 15% reduction in CO<sub>2</sub> emissions.

The other key element of the powertrain that can be modified to reduce a vehicle's CO<sub>2</sub> emissions rate is the transmission. New designs using more gears or continuously variable ratios can reduce a vehicle's CO<sub>2</sub> emissions rate by up to 6%.

Diesel engines offer GHG emissions reductions because of their inherently higher fuel efficiency compared to conventional gasoline engines and the lower level of energy and emissions entailed in producing diesel fuel rather than gasoline. Applied in a large personal vehicle such as an SUV, diesel engines could offer CO<sub>2</sub> emissions reductions of up to 30%. The main challenges facing greater use of diesels are emissions control difficulties, particularly for achieving the very low levels of NO<sub>x</sub> emissions required by California's regulations. Particulate filters and low-sulfur fuel would also be required. Development of the needed diesel emissions control systems is underway.

Gasoline direct injection (GDI) is an advance in technology that enables gasoline engines to approach efficiency levels similar to those of diesel engines. Among the more efficient GDI engines are those that involve lean-burn operation; however, such designs also have a NO<sub>x</sub> cleanup challenge. Versions of GDI using a homogeneous charge can use three-way catalysts to meet tight emissions standards, providing high efficiency when implemented in a turbocharged, downsized engine. GDI offers CO<sub>2</sub> emissions reductions ranging from 5% to 20% depending on how it is implemented and the base engine to which it is compared. Costs are estimated at \$300–\$400.

Two advanced engine designs still being researched are homogeneous charge compression ignition (HCCI) and Controlled Auto-Ignition (CAI). A number of technical challenges must be overcome before HCCI or CAI engines can be commercialized, but they offer the potential for diesel-level efficiency with very low NO<sub>x</sub> emissions.

An integrated starter-generator (ISG) is a device that takes the place of the current starter motor and alternator and offers the potential for a variety of fuel-saving strategies, including engine shut-off during idle, more efficient electrical generation and the potential for upgrading accessories to 42 volts, allowing more efficient operation. Tested ISG systems have demonstrated CO<sub>2</sub> emissions reductions from 8% up to 20%, with higher reductions achieved in a system with a downsized engine and other efficiency features enabled by the technology.

Hybrid-electric vehicle (HEV) vehicle design, combining a combustion engine with elements of an electric-drive powertrain, offers a range of CO<sub>2</sub> emissions reduction possibilities depending on the design and application. The first hybrids to reach the U.S. market have demonstrated 23% to 30% reductions in fuel consumption and CO<sub>2</sub> emissions, but bear significant price premiums on the order of \$3,500 for compact cars. Other hybrid designs can offer even greater CO<sub>2</sub> emissions reductions and the option of a significant all-electric (zero tailpipe emissions) driving range, but at higher cost.

Another category of technologies reduces a vehicle's energy loads, that is, the amount of energy needed at the wheels to move the vehicle or needed to power accessories such as heating, air conditioning and lighting. Reducing vehicle loads reduces the output required from the powertrain and therefore

complements powertrain efficiency as an approach for reducing CO<sub>2</sub> emissions. Load reduction options include reducing vehicle mass without making the vehicle smaller, reducing aerodynamic drag and tire rolling resistance, and improving the efficiency of vehicle accessories. Mass reduction provides the largest potential benefits, through the use of lightweight materials and, for truck-based vehicles, shifting to car-based platforms (as seen in the emerging market for crossover vehicles).

The overall impact of the variety of technologies for reducing CO<sub>2</sub> emissions is best assessed through systems analysis using engineering simulation tools. Such analysis can account for the interactions among technologies, positive or negative, in order to estimate the net emissions reduction achievable by applying new technologies. Results depend on the technologies considered to be appropriate and affordable for a given vehicle application. Systems analysis results presented at the symposium suggest potential reductions of 20% to 40% in CO<sub>2</sub> emissions from light duty vehicles operating on gasoline. Additional reductions are possible through dieselization.

Alternative (non-petroleum) fuels are another approach to GHG emissions reduction. Assessing the net reductions from alternative fuels requires analysis of the full fuel cycle, also known as "well-to-wheels" analysis. Results depend on details of a given resource/fuel-use "pathway," including the primary energy resources from which the fuel is derived, the processes used to produce and distribute the fuel, and the efficiency of the powertrains that utilize the fuel on the vehicle. Renewable fuel cycles designed for near-zero net GHG emissions, as proposed for hydrogen fuel cell cars, have the potential to greatly reduce motor vehicle GHG emissions. Other fuels, such as ethanol or methanol, that can be produced from renewable resources can also greatly reduce GHG emissions. Cost and resource constraints (including land use) are issues for all such alternatives, which must compete with the established petroleum-based motor fuel pathway. The reductions that can be achieved within any given time frame depend on the particular alternative fuel pathway chosen.

In summary, many technological options exist for reducing GHG emissions from personal motor vehicles and a range of new options are under development. All options face a variety of issues regarding cost and effectiveness. A substantial pool of expertise, reflected by the information presented at the symposium, is available to help policy makers assess the options that should be considered when developing programs to control GHG emissions from cars and light trucks.

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# Introduction

On July 22, 2002, the governor of California signed Assembly Bill 1493 (AB 1493) to limit greenhouse gas (GHG) emissions from passenger cars and light duty trucks. The bill requires the California Air Resources Board (CARB) to adopt regulations to achieve the maximum feasible, cost-effective reductions of GHG emissions by new passenger cars and light-duty trucks. Regulations must be adopted by January 1, 2005, and will only apply to new vehicles manufactured in model year 2009 and later.

As part of the process to implement AB 1493, CARB is assessing the technologies (those existing today and those to be developed in the timeframe considered in the bill), that can be used to reduce car and light truck GHG emissions. CARB hosted the symposium<sup>1</sup> to discuss current and emerging GHG emission reduction technologies. Symposium speakers included representatives from auto manufacturers, supplier companies, academia, non-governmental organizations and consultancies. Topics included technologies for reducing all significant GHG emissions, effects of new technologies on vehicle performance and the potential of alternative fuels to reduce these emissions. Appendix A shows a list of all the symposium presentations. Following a brief overview of automotive GHG emissions in the state, this report summarizes the findings presented at the symposium.

## Greenhouse gas emissions in California

Gross GHG emissions in California (i.e. emissions from all sources, without accounting for removals by sinks) were 428 million metric tons of CO<sub>2</sub>-equivalent in 1999. CO<sub>2</sub> emissions from fossil fuel combustion, cement production and other sources accounted for the majority (roughly 85%) of emissions. CH<sub>4</sub> and N<sub>2</sub>O were the next most abundant greenhouse gases emitted, 8% and 6%, respectively. As a group, HFCs, perfluorocarbons and sulfur hexafluoride account for 2% of the statewide GHG emission inventory (CEC 2002).

## Greenhouse gas emissions from light duty vehicles

Transportation is the economic sector with the highest contribution to GHG emissions in California. It mainly contributes to CO<sub>2</sub> emissions but imperfections in the combustion process also yield N<sub>2</sub>O and CH<sub>4</sub>. Based on the most recent state data from CEC (2002), the transportation sector accounts for 58% of CO<sub>2</sub> emissions, 26% of N<sub>2</sub>O emissions and 1% of CH<sub>4</sub> emissions in California. These estimates correspond to 48% of total GHG emissions in the state. This contribution differs from the nation as a whole, where transportation represents 33% of GHG emissions (DeCicco and An 2002). Combustion of motor fuel by automobiles—including both cars and light trucks—is the biggest source within

<sup>1</sup>[www.arb.ca.gov/gcc/techsem/symposium.htm](http://www.arb.ca.gov/gcc/techsem/symposium.htm)

the transportation sector, accounting for 37% of total statewide CO<sub>2</sub> emissions as of 1999. Other greenhouse gases such as HFC-134a are emitted from leaks, servicing and scrapping of automotive air conditioners.

Table 1 shows the direct greenhouse gas emissions for a typical car and light truck meeting California low emission vehicle standard (LEV I). Direct emissions refer to those occurring at the vehicle itself, excluding emissions associated with producing the fuel and manufacturing the vehicle. The various gases emitted by a motor vehicle have different impacts on global warming per equal mass; estimates of these impacts are given by what is termed the global warming potential (GWP). In Table 1, emissions of non-CO<sub>2</sub> gases are translated into their CO<sub>2</sub>-equivalent (CO<sub>2</sub>eq) values by taking into account their GWP as given in CEC (2002).

A complete GHG emissions picture for motor vehicles would include the emissions during production of the vehicle and the fuel. Lifecycle analysis can provide such estimates, covering direct emissions from vehicle operation as well as emissions from steel production, gasoline refining and the many other industrial processes associated with cars and their fuel. About 68% of automotive GHG emissions are direct emissions during vehicle use, 21% are associated with gasoline production and distribution, and 11% are associated with vehicle manufacturing (DeCicco & An 2002, Figure 9). The symposium covered emissions associated with fuel production when alternative fuels were discussed, but did not address options for reducing the emissions from fuel cycles themselves; neither did it address options for reducing emissions from vehicle manufacturing (both of these can be considered part of the industrial rather than transportation sector).

TABLE 1  
**Greenhouse Gas Emissions for vehicles meeting LEV I standards  
 (g CO<sub>2</sub>-eq/mile)**

	<b>Fuel Economy<sup>a</sup></b>	<b>CO<sub>2</sub><sup>b</sup></b>	<b>N<sub>2</sub>O<sup>c</sup></b>	<b>CH<sub>4</sub><sup>c</sup></b>	<b>HFC-134a<sup>d</sup></b>	<b>Total</b>
Car	28.2 mpg	361	9	0.8	16	387
Light Truck <sup>e</sup>	20.8 mpg	492	12	1.0	16	521
Avg LDV	24.3 mpg	420	10	0.9	16	447

Notes: <sup>a</sup>New fleet test fuel economy, MY 2000 averages from EPA (Hellman and Heavenrich 2003); <sup>b</sup>Direct CO<sub>2</sub> emissions only, assuming 8.7 kg CO<sub>2</sub>/gal of gasoline and EPA's adjusted average fuel economy values; <sup>c</sup>N<sub>2</sub>O and CH<sub>4</sub> estimates from CEC, 2002; <sup>d</sup>HFC-134a estimates by Siegl and Wallington (2002) including service and scrapping leakages, assuming vehicle mileage of 12,000 miles/year; <sup>e</sup>Gross vehicle weight of up to 8,500 lbs.

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## Vehicle technologies to reduce GHG emissions

Different technologies are summarized in the order they were presented during the symposium. Each group of technologies is introduced with a brief discussion of how they affect the emissions of the particular greenhouse gases they influence. This is followed by a description of the ways in which GHG reduction is achieved using the technology and information provided by the speakers. The following is a classification of the different technologies considered at the symposium:

- Technologies to reduce HFC emissions
- Technologies to reduce N<sub>2</sub>O and CH<sub>4</sub> emissions
  
- Technologies to reduce CO<sub>2</sub> emissions
  - Powertrain and drivetrain technologies
    - Conventional technologies (near-term conventional)
    - Vehicle technologies (load reduction)
    - Advanced powertrain modifications (longer-term conventional)
    - Hybrid electric and fuel cell vehicles
    - Whole vehicle-system analysis
  - Alternative fuels

### Reducing HFC emissions

HFCs are a class of chemicals containing hydrogen, fluorine and carbon used as refrigerants in air conditioners. In the mid-1990s, a particular HFC, HFC-134a, replaced earlier refrigerants containing chlorofluorocarbons (CFCs). Unlike CFCs, HFCs do not contain chlorine and therefore do not destroy the Earth's protective stratospheric ozone layer. Although it does not threaten stratospheric ozone, HFC-134a is a powerful greenhouse gas with a global warming potential 1,300 times stronger than that of CO<sub>2</sub>.

An automotive air conditioner (A/C) consists of a closed loop system through which the refrigerant is pumped by a compressor, cooling the passenger compartment and rejecting waste heat to the outside air through a condenser. A typical late-model automotive A/C system contains about 24-35 ounces of refrigerant. Being under pressure and not perfectly sealed, leaks can occur throughout the system (e.g., at the compressor shaft seals, O-rings, hoses and fittings).

Siegl et al. (2002) reported statistics on HFC-134a emissions from automotive A/C systems. Refrigerant leaks from seals and fittings can occur when

a car is parked, amounting to roughly one ounce per year for an average car.<sup>2</sup> Larger releases are estimated to occur during service and scrappage, averaging four ounces per year over the life of a typical car. Adding these estimates suggests total HFC-134a emissions from an A/C-equipped vehicle averaging about five ounces per year. When the global warming potential is taken into account, this emission corresponds to 16 gCO<sub>2</sub>eq/mile if we assume an average mileage of 12,000 miles/year. This estimate is 4% of the 447 gCO<sub>2</sub>/mile of direct fuel consumption-related emissions for an average light duty vehicle, which includes the fuel consumed to run and carry the weight of the A/C system.

James Baker of Delphi Corporation discussed issues associated with automotive A/C HFC-134a emissions during the symposium. He noted that the U.S. Clean Air Act prohibits release of HFC-134a to the atmosphere during air conditioner service and vehicle scrappage. HFC-134a emissions are minimal for servicing when professional technicians properly recover and recycle the refrigerant onsite. However, since HFC-134a can be purchased by the general public, who lack the equipment necessary to properly capture and recycle refrigerants, the venting prohibition has not been duly enforced for "do it yourself" (DIY)'ers. Baker also noted that HFCs are released when DIY'ers refill their A/C systems using off-the-shelf 12-ounce cans that poorly match the actual refrigerant content of the systems.

During the symposium, Baker as well as Ward Atkinson of Sun Test Engineering presented options for reducing the HFCs releases from vehicle A/C systems. Baker summarized the European Commission's program for reducing greenhouse gas emissions from mobile air conditioners, drawing on information presented at a meeting on the topic in Brussels in February 2003. Broadly speaking, there are three approaches: 1) reducing leaks by improving the containment efficacy of the system; 2) changing the refrigerant to one with a lower global warming potential; and 3) reducing refrigerant releases during servicing and scrappage.

#### REDUCING HFC-134A SYSTEM LEAKAGE

A variety of technical refinements to existing HFC-134a mobile A/C systems are feasible for reducing leaks. Options include hermetically sealed compressors and electronic control of the system. An advantage for the industry is that refining existing, known technology keeps costs to a minimum. No safety issues are related to the use of HFC-134a. The technology also has the potential to improve A/C energy efficiency and hence reduce indirect CO<sub>2</sub> emissions. A limitation of this approach is the high GWP associated with residual HFC-134a emissions, which cannot be entirely eliminated.

<sup>2</sup> Background information on automotive A/C refrigerant emissions is taken from Siegl et al. (2002). Regarding the system leakage from fitting and seals, the Siegl et al. estimate of one ounce is lower than that suggested by recent European measurements that indicate a leakage rate of 57 g/yr (2 ounces/year), as reported by James Baker during the symposium.

## ALTERNATIVE REFRIGERANTS

Two alternative refrigerants are being considered by the industry for replacing HFC-134a: HFC-152a and CO<sub>2</sub>.<sup>3</sup>

### *HFC-152a*

Some systems suppliers and car manufacturers have started to consider the use of HFC-152a as an alternative to HFC-134a. These two chemicals are similar, but HFC-152a has two hydrogen atoms replacing two fluorine atoms in its structure. HFC-152a has a lower global warming potential (120 instead of 1,300) and it offers higher cooling performance and potentially higher efficiency. Costs and materials compatibility considerations are similar. The downside of HFC-152a is that it is mildly flammable and, if ignited, its decomposition products are toxic.<sup>4</sup> These risks could be minimized by incorporating an effective passenger cabin safety system or by designing the A/C system with a secondary loop, so that the refrigerant is isolated from the heat exchanger that cools the interior of the vehicle. However, the secondary loop option offsets most of the advantages: a system running with a secondary loop would be more expensive and less efficient in terms of energy consumption.

### *CO<sub>2</sub>*

Carbon dioxide itself can serve as a refrigerant. A clear advantage is that all HFC emissions would be eliminated and the residual CO<sub>2</sub> emissions from leakage and service would be of little global warming consequence. A CO<sub>2</sub>-based system can also be used as a supplemental heat source, which is attractive for vehicles with highly efficient engines that produce little waste heat for cabin heating in cold weather. However, the technology is still in development, with technical and safety issues that need to be resolved before full-scale commercialization is feasible. CO<sub>2</sub> systems operate at high pressure (five to ten times higher than the actual HFC-134a system). Therefore, there are risks of CO<sub>2</sub> leaks to the cabin due to the effects of CO<sub>2</sub> on the central nervous system. Efficiency appears comparable to that of HFC-134a systems, though it is not yet proven in real-world conditions. The main challenges of a CO<sub>2</sub>-based system relate to its higher cost vs. HFC-134a, its reliability using high pressures and the safety of service and operation.

Table 2 summarizes information on the emissions reductions and costs as presented by Baker. For reference, a typical automotive A/C system costs \$300–\$600 depending on the size of the vehicle.<sup>5</sup>

<sup>3</sup> A third option, the use of hydrocarbons, is under consideration in Europe but is not being considered in United States due to safety concerns.

<sup>4</sup> If HFC-152a burns the end result is hydrofluoric acid which is toxic and thus dangerous to human health.

<sup>5</sup> This is the cost of parts as delivered by suppliers to OEM (James A. Baker, personal communication).

TABLE 2  
**Emissions reduction and cost estimates for automobile air conditioners**

<b>A/C System Choice</b>	<b>Reduced Direct Emissions</b>	<b>Reduced Indirect Emissions</b>	<b>Added Cost (euros)*</b>	<b>Time to Market (years)</b>	<b>Issues</b>
HFC-134a	Baseline	Baseline	Baseline	Current	--
Improved 134a	50%	25%	20	1-3	none
HFC-152a	94%	10%	15	4-6	
Secondary loop 152a	96%	Baseline	40		Market Acceptance
Future 152a	94+%	30+%	35		
CO <sub>2</sub>	100%	1%	40-180**	6-11+?	Technical
Future CO <sub>2</sub>	100%	?	?		hurdles

Notes: \* 1 Euro = 1.1 US\$ (March 11th 2003); \*\* Excludes retooling

Source: derived from "MAC Summit Review". Baker, 2003

### REDUCING EMISSIONS DURING SERVICE AND SCRAPPAGE

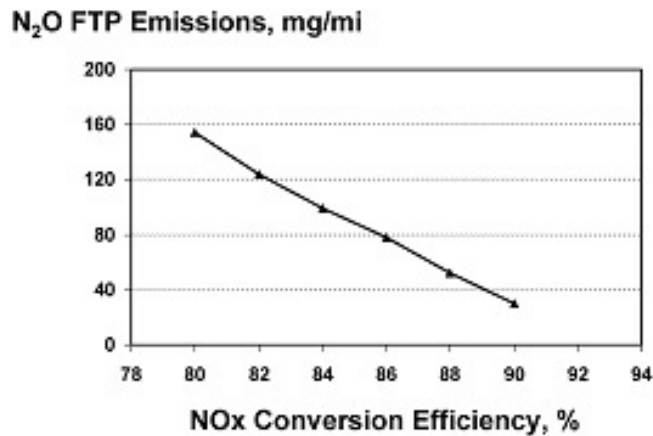
The third approach for reducing automotive A/C emissions relates to better practices in servicing and disposal, described in Ward Atkinson's presentation at the symposium. Options include improving refrigerant recovery during service and scrapping; designing more complex systems that discourage do-it-yourselfers from refilling refrigerant themselves; and improving the service technician training. No estimates were presented for the amount of HFC emissions that could be avoided through improved service and scrapping procedures.

### Reducing N<sub>2</sub>O and CH<sub>4</sub> emissions

N<sub>2</sub>O is emitted directly from motor vehicles and its formation is highly dependent on temperature and the type of emission control system used. Its global warming potential is 310 times that of CO<sub>2</sub>.

The high temperatures of the internal-combustion engine are sufficient to form NO and NO<sub>2</sub> (the two forms of "NOx," a major pollutant that contributes to smog), but produce little or no N<sub>2</sub>O. Temperatures favorable for N<sub>2</sub>O formation are achieved inside catalytic converter systems, especially during cold-start conditions when engine temperatures are lower. Catalyst efficiency (the amount of NOx that is removed) and age are also important factors in N<sub>2</sub>O formation. At higher efficiencies and lower ages, N<sub>2</sub>O formation is lower. Figure 1 shows this dependence on catalyst NOx efficiency and N<sub>2</sub>O formation.

FIGURE 1  
**Strong Correlation Between TWC NOx Efficiency and N<sub>2</sub>O Emissions**



Ref. SAE 2000-01-1952



This graph shows N<sub>2</sub>O emissions over the Federal Test Procedure (FTP) as a function of a three-way catalyst's (TWC) effectiveness in removing NO<sub>x</sub> from an automobile's exhaust stream.  
Source: Kubsh presentation

CH<sub>4</sub> is emitted from any internal combustion engine using hydrocarbon fuels as one of the products of incomplete combustion. Emissions of CH<sub>4</sub> are a function of the type of fuel used, the design and tuning of the engine, the type of emission control system, the age of the vehicle and other factors. CH<sub>4</sub> is difficult to oxidize catalytically and so emissions control systems are not as effective in cutting CH<sub>4</sub> emissions as they are in cutting non-methane hydrocarbons. Although CH<sub>4</sub> emissions from gasoline vehicles are small in terms of global warming potential when compared to N<sub>2</sub>O emissions, they can be high in natural gas vehicles, considering that CH<sub>4</sub> is the primary component of natural gas. Because methane's global warming potential is 21 times higher than that of CO<sub>2</sub>, special attention to CH<sub>4</sub> emissions control is needed to realize the full GHG reduction potential of natural gas vehicles.

In California, mobile sources emitted an estimated 6.2 MMT CO<sub>2</sub>eq of nitrous oxide and 0.4 MMT CO<sub>2</sub>eq of methane in 1999 (CEC 2002), or 3% and 0.2%, respectively, of the state's transportation GHG inventory.

Joseph Kubsh (of the Manufacturers of Emission Controls Association, MECA) presented information on the advanced emissions control systems that will be adopted to meet the pollutant emission controls associated with LEV II regulations in California. The technologies include layered three-way catalytic converter coating architectures, high cell density substrates and materials having reduced deterioration. According to Kubsh, the improved controls will drive down N<sub>2</sub>O emissions from vehicles so that there is no need to pursue special controls for N<sub>2</sub>O emissions. Nevertheless, he presented a technology used in the production of adipic acid (used for Nylon 6,6 production) that catalytically decomposes N<sub>2</sub>O to form N<sub>2</sub> and O<sub>2</sub>. He noted that although decomposition catalysts have not been tested in automotive conditions, such systems would face durability challenges due to high exhaust temperatures and sensitivity to fuel sulfur content.

Alex Lawson (of Teleflex GFI Control Systems LP) presented a similar view when considering the reduction of CH<sub>4</sub> emissions from natural gas vehicles. According to his presentation, progress in the area of NO<sub>x</sub> reduction can lead to CH<sub>4</sub> emission reduction. New catalyst and engine calibration technologies show that methane emissions from natural gas vehicles can be reduced to close to their gasoline counterparts using improved catalyst designs (CH<sub>4</sub> reductions of 72% have been seen in tests). Such designs would use the same packaging and conventional metal loadings, but provide higher internal surface areas.

## Reducing CO<sub>2</sub> emissions

The CO<sub>2</sub> emitted by a motor vehicle is the product of three factors: the amount of driving, the vehicle's fuel consumption rate, and the carbon intensity of the fuel consumed. The amount of driving depends on the nature of the transportation system, land use and the availability and cost of alternative travel choices, all issues that were not discussed at the symposium. The fuel consumption rate is the inverse of fuel economy (miles per gallon, or mpg) and so it depends on a vehicle's design and its energy efficiency. Finally, carbon intensity is how much CO<sub>2</sub> is emitted per unit of fuel consumed and depends on the type of fuel. For California gasoline, roughly 8.7 kg (19 lbs) of CO<sub>2</sub> is emitted from complete combustion.<sup>6</sup> The exact value depends on the particular fuel formulation. The symposium addressed technologies for reducing these two factors—the fuel consumption rate and fuel carbon intensity—that depend on the design of a vehicle and its type of fuel.

The consumption of fuel energy by a vehicle depends on two main factors: the vehicle load and the energy-efficiency of the powertrain (engine plus transmission). The vehicle load is the propulsion energy needed to overcome: 1) inertia (weight) when accelerating or climbing hills; 2) the resistance of the air to the vehicle motion (aerodynamic drag); and 3) the rolling resistance of the tires on the road as well as the energy needed to operate vehicle accessories. Powertrain efficiency determines the amount of energy contained in the fuel that is finally delivered to the wheels. Minimizing vehicle load requirements and maximizing the powertrain efficiency achieves minimum fuel consumption and therefore minimizes this key cause of CO<sub>2</sub> emissions.

A typical gasoline spark ignition (SI) engine is illustrated schematically in Figure 2. Readers can refer to this diagram to locate some of the areas discussed by symposium presenters as offering opportunities to improve engine efficiency. Any number of standard texts can be referenced for explanations of how engines work (e.g., Stone [1992], Heywood [1988]).

<sup>6</sup> Estimate provided by CARB staff member Jim Guthrie (personal communication to author, 8/21/2003) based on data for typical California test fuels.

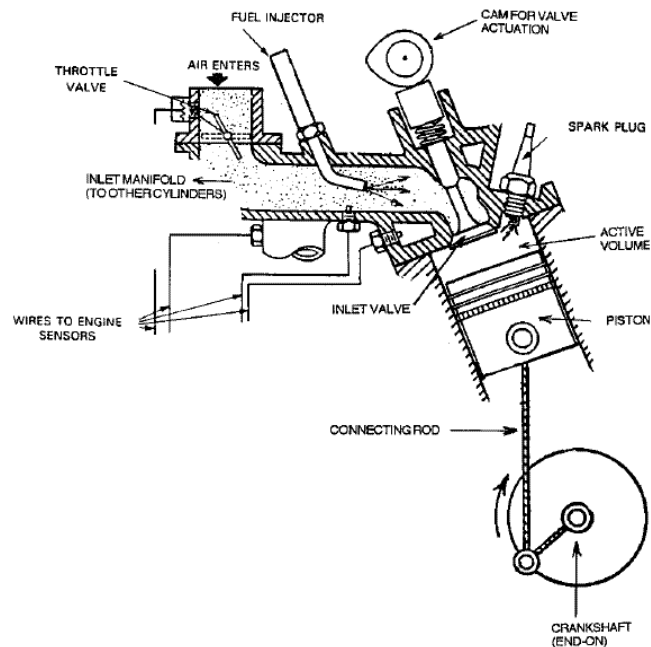
## POWERTRAIN AND DRIVETRAIN MODIFICATIONS

A variety of engine refinements were proposed at the symposium that improve the efficiency of the powertrain and drivetrain systems. Some involve subtle or minor changes to gasoline engines while others consist of more radical changes to engine operations and the thermodynamic cycle.

### *Minor changes to improve the efficiency of a large engine*

Loren Beard of DaimlerChrysler and Marc Ross from the University of Michigan separately discussed several low-cost technologies under study at DaimlerChrysler to improve the fuel economy of the 4.7L V8 engine that is found in the Dodge Durango and the Jeep Grand Cherokee four-wheel drive SUVs. In the Durango, a midsized SUV, this engine now delivers an average of 18 mpg. After examining all the factors that influence engine fuel efficiency, Dr. Beard identified eight areas of improvement, discussed below. Dr. Ross also discussed these improvement option, noting that his analysis was based in part by that given by DaimlerChrysler (2002).

FIGURE 2  
**Sketch of engine cylinder and inlet system**



Source: Ross presentation

Dr. Ross presented estimates of the reductions in fuel consumption associated with each of these areas (his estimates are given in parentheses in the beginning of each paragraph). He also presented a summary estimate for the effect of these measures plus some other minor refinements that reduced the load requirements of the vehicle (discussed below, on p.21). Dr. Ross estimated a reduction of fuel consumption by 20% in the city driving cycle for a total cost of less than \$500. However, he cautioned that in spite of the modest cost and excellent results, automakers are unlikely to market engines reflecting this degree of fuel consumption reduction unless such reductions are required, even though they might adopt some of the measures over time.

**Increased compression ratio (3% to 4%).** The compression ratio is the ratio between the maximum and the minimum volumes achieved inside the cylinder. of an internal combustion engine and it is one of the basic parameters affecting engine efficiency. In gasoline engines, compression ratio is limited by the need to avoid knock (preignition and detonation). Higher compression ratios lead to knocking because they increase the temperature of the cylinder charge (mixture of air and fuel). Beard identified three technology refinements that improve charge cooling and enable higher compression ratios (from 9.0 to 10.5) without knock risks.

**Charge motion control; increase low speed efficiency (4%).** The efficiency of an internal combustion engine is low at low engine speed and load, in part because of poor mixing of the charge. This has been corrected in many engines by using two intake valves per cylinder and almost closing one of them to enhance swirl (special movement inside the cylinder that enhances good mixture). Chrysler engineers invented a less costly approach applicable to their engines by installing a baffle valve before each intake port to create turbulence ensuring good mixing—and faster flame propagation—at low engine loads, hence improving efficiency.

**Friction loss reduction (3% to 4%).** Dr. Beard presented several design changes to lower friction losses at no extra cost: crankshaft offset, reduced oil-ring tension and shortened coolant jacket. An offset crankshaft (a crankshaft whose center is not in line with the cylinder)<sup>7</sup> reduces friction at cylinder walls. A shortened coolant jacket permits more uniform cylinder wall temperature, which in turn enables reduced tension in the oil ring. Normally, the coolant jacket extends the full length of the cylinder. This full-length jacket results in the top of the cylinder being undercooled, while the bottom—which is hardly heated at all—is overcooled. Overcooling of the bottom of the cylinder means that the oil is overly viscous, increasing friction loss. Also, an improved air-oil separator in the crankcase ventilation system permits lower-viscosity oil, reducing oil-ring tension and cutting friction losses.

<sup>7</sup> The crankshaft is the mechanism that transmits the energy of the cylinder to the drive system.

**Parasitic loss reduction (1%).** Parasitic loss is energy consumed by the working parts of the engine itself. One such loss is the oil pump. Oil pumps are sized for worst-case scenarios. An old engine that is idling following extended high-speed travel represents such a scenario. The engine speed and the oil viscosity are low, so the pump must be sized to ensure adequate oil pressure in this operating condition. For this reason, pump efficiency at low engine speeds is very important. Dr. Beard stated that a pump with a favorable size improves its efficiency at low engine speeds.

### *Variable Valve Control*

Valves are used in an engine to allow flow into and out of the cylinder at the proper time in the cycle. The inlet valve draws in the air-fuel mixture during the intake stroke. After the compression and power strokes have been completed, the exhaust valve is open to let out the burnt gases. In a conventional gasoline engine, the mechanism that operates the valves is called the camshaft. It is driven by, and rotates at half the speed of, the crankshaft, which is connected to the pistons.

In conventional engines, valve timing (when the valves open and close) and lift (how much they open) are fixed functions of crank movement, so the same timing and lift are used at all engine speeds and loads. Variable Valve Control (VVC)<sup>8</sup> controls valve position depending on operating conditions, allowing more optimum performance at different engine speeds. VVC can also reduce the need for throttling at low power.

Different degrees of flexibility can be incorporated into VVC designs. Some systems rely on a simple phase shift of the intake camshaft (addressing only timing); others incorporate completely variable valve timing and lift profiles at different speed/load conditions. Peter Hofbauer of FEV presented a range of VVC strategies together with the fuel consumption reductions that they can achieve. The following options were presented, ordered by their degree of flexibility:

- **Inlet and exhaust phasing:** This technology allows a change in the timing of when the valves are opened and closed but does not allow changes in the duration or lift of the valve openings.
- **Cylinder deactivation:** Through a mechanical system, some valves (and hence cylinders) can be deactivated when low power is needed. This technology is described separately in a following section.
- **Mechanically Variable Valve Train:** This technology uses camshaft contours that are machined to allow different degrees of lifting (from 0 to some maximum lift).
- **Electromechanical Valve Train (EMVT), inlet only:** This technology involves the use of electromechanical mechanisms to open and close an inlet valve that

<sup>8</sup> Some presenters referred to VVC as Variable Valve Timing (VVT); these terms are sometimes used synonymously but occasionally VVT is used to refer only to versions of VVC that control just timing (cam phasing) without controlling valve lift (how much the valve opens).

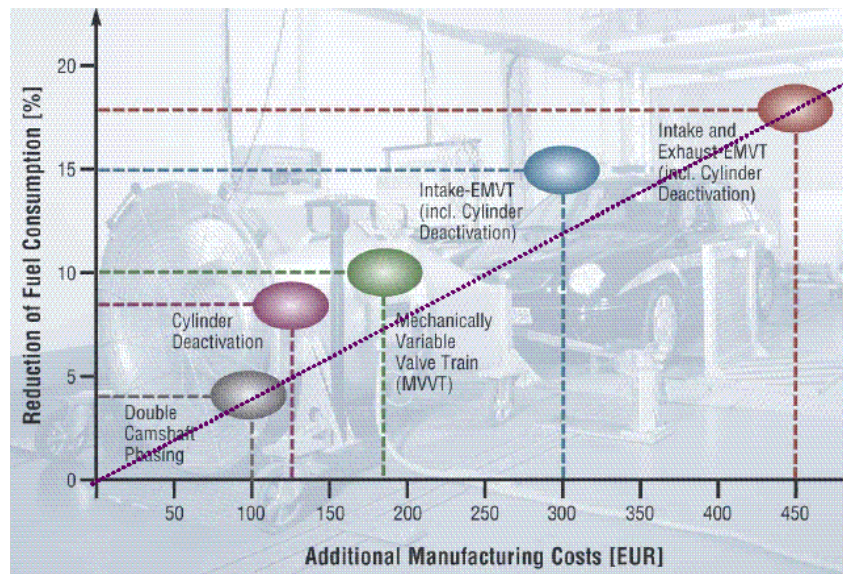
oscillates between two springs. There is unlimited range for timing, duration and lift performance of the intake valve.

- **Inlet and exhaust EMVT:** With this technology both inlet and exhaust valves are driven electromechanically, allowing complete freedom for precisely controlled valve operation and unthrottled control of engine load.

A factor that has limited the use of EVMT is the noise of the high-speed mechanisms operating the valves. According to Hofbauer, there have been recent improvements that reduce this limitation.

Figure 3 represents the increasing variable production costs and potential reduction in fuel consumption that can be achieved with variable valve technologies. Short of cylinder deactivation, variable valve timing can reduce fuel consumption by up to 10%.

FIGURE 3  
**Different valve train configurations: reduction in fuel consumption and production associated costs**



Note: 1 Euro = 1.1 US\$ (March 11<sup>th</sup> 2003)  
Source: Hofbauer presentation

In addition to the VVC options described by Prof. Hofbauer, Jamie Turner of Lotus Powertrain Research described another variable valve timing system termed the Active Valve Train (AVT). AVT entails an electrohydraulic mechanism and has been used as a research tool by Lotus, enabling investigation of advanced combustion techniques such as CAI and HCCI (described below). Production versions of the electrohydraulic active valve train (Lotus "ProAVT")

are also under development.<sup>9</sup> The camless and throttleless operation offered by electrohydraulic VVC also can be used to implement a variety of optimizations for conventional combustion systems, including variable displacement, variable compression, reduced idle speed and catalyst temperature control, among others.

Turner noted that the highly precise, fully variable control of intake and exhaust flows enabled by AVT technology can be combined with gasoline direct injection (GDI, also described below) to enable complete manipulation of all fluid flows in the cylinder. Such levels of control, which can be applied to each cylinder independently, will enable precise load matching and therefore even greater levels of CO<sub>2</sub> reduction.

### *Cylinder deactivation*

As described above, a special version of VVT allows the deactivation of selected cylinders by keeping their valves closed throughout the cycle. By deactivating some cylinders at low power levels, the other cylinders have to operate at higher load. This higher load puts the active cylinders' operating point in a more efficient region, reducing their pumping losses while eliminating the pumping losses of the deactivated cylinders.<sup>10</sup>

Roland Kemmler (from DaimlerChrysler) introduced the technology being developed for Mercedes-Benz's V-8 and V-12 engines to "cut off" or deactivate half the cylinders during low power conditions. Due to harshness considerations, Mercedes-Benz is developing this technology only for large engines, but its design enables deactivation during idle as well as low-load running conditions. Kemmler described the Mercedes-Benz cylinder cut-off mechanism which uses a hydraulically activated locking pin in the valve train. When operated, the pin connects or disconnects the valve from its operating cam. Mercedes-Benz tests show a 6% to 10% improvement in fuel economy through the use of cylinder deactivation in normal driving cycles.

One of the limitations to widespread use of cylinder deactivation is the loss of comfort associated with the switch over between the full- and half-cylinders' operating modes. DaimlerChrysler has developed automated corrective controls to achieve acceptable comfort levels.

Dr. Hofbauer also addressed cylinder deactivation, noting that it can be considered for smaller engines, such as 4-cylinder models, when designed appropriately. However, in smaller engines (4's and 6's), vibration and roughness concerns limit the use of cylinder deactivation to restricted operating conditions and can prevent its use during idle.<sup>11</sup> Hofbauer's estimates (Figure 3) indicate that the combination of cylinder deactivation with variable valve timing for both

<sup>9</sup> See Lotus (2003) news release issued later in the year announcing a development agreement for a version of the ProAVT technology described by Mr. Turner during the symposium.

<sup>10</sup> Pumping loss refers to the energy used to draw the air-fuel mixture into the cylinder and to push the burned gases out. Pumping loss increases when air inflow is throttled (restricted) to reduce engine output when full power is not needed. The loss can be significant at low power conditions, such as steady cruise velocity or idle.

<sup>11</sup> Honda deactivates three of four cylinders on the Civic Hybrid but only during non-loaded deceleration when no engine power is needed.

intake and exhaust can reduce fuel consumption by 18% for a manufacturing cost of roughly \$450 for a 4-cylinder engine.

### *Turbocharging and engine downsizing*

A turbocharger is a system that uses the energy from the exhaust gases to run a turbine that then drives a compressor that forces air into the cylinders under higher pressure. Turbocharging is a form of what are generically termed "boosting" technologies, the other approach being *supercharging*, in which the compressor is driven by mechanical or electrical devices rather than an exhaust gas turbine. Forcing more air into the cylinder improves the power that can be obtained from a given size engine, which is why boosting technologies are popular approaches to enhance the speed performance of cars. However, if a turbocharged engine is downsized (reducing its displacement) so as to still achieve the same performance of the original engine, fuel consumption can be reduced.

S.M. Shahed from Garret presented this technology at the symposium and stated that CO<sub>2</sub> emission reductions on the order of 20% are possible with engine downsizing and turbocharging while maintaining performance. Shahed pointed out that this technology is widely used in Europe with small engines. For larger engines i.e. SUVs, turbochargers have limited application today because at idle (or low speeds) there is not enough energy in the exhaust gases to provide the required launch power and the engine hesitates when the accelerator is pressed (this problem is called turbo-lag). Garret is currently developing an electrically assisted turbocharger that will overcome the turbo-lag problem for large engines. Reduction of CO<sub>2</sub> emissions in the order of 15% for SUVs with downsized engines is expected with the use of this technology by year 2007.

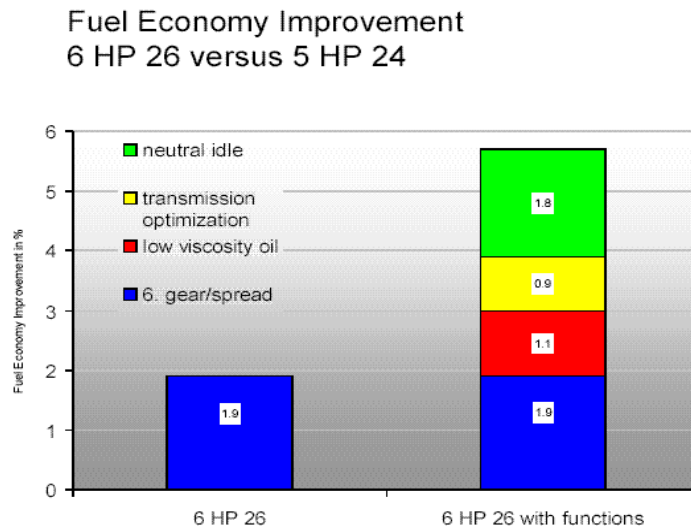
### *Transmission improvements*

The transmission system is designed to improve the efficiency of a given engine by allowing it to operate at both a lower speed, with lower mechanical friction, and a higher load, with lower pumping losses. Increasing the number of gear steps between the available limits (that is, moving to five or more speeds in an automatic transmission), is one measure to improve transmission efficiency and is the current trend for automobile transmissions. Herbert Mozer from ZF Group presented two technologies that increase the number of gears for automatic vehicles without compromising vehicle performance.

Six-speed automatic transmissions have an added gear compared to the 5-speed automatics now in use. The addition of a gear increases the total gear ratio and improves fuel economy by 2% compared to a 5-speed automatic. If other operational and control refinements are included, the fuel economy improvement is close to 6%. Figure 4 shows the fuel economy improvements on the European Driving Cycle associated with these measures. According to Mozer, this configuration enables simultaneous performance improvements, leading to about 4% better acceleration, in addition to the improved fuel economy.

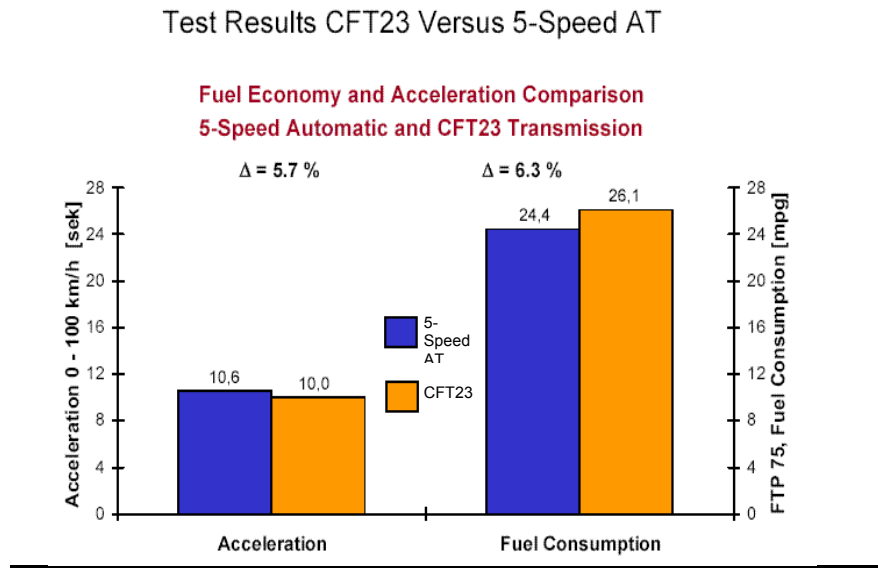
A continuously variable transmission (CVT) offers an infinite choice of gear ratios between minimum and maximum levels, allowing optimization of engine operating conditions to maximize fuel economy and increase maximum power. Mozer presented the fuel economy and performance advantages of CFT23, a belt CVT transmission system currently under production at ZF Batavia, shown in Figure 5. Tests indicate the potential for simultaneous improvements in both acceleration performance and fuel economy on the order of 6%.

FIGURE 4  
**Fuel economy improvements of a 6-speed over a 5-speed automatic transmission**



Source: Mozer presentation

FIGURE 5  
**Acceleration and fuel economy comparisons between a 5-speed automatic and a continuously variable transmission**



Note: FTP 75 is the U.S. EPA urban driving cycle; the right hand axis should be labeled fuel economy instead of fuel consumption.

Source: Mozer presentation

### *Diesel engines*

Diesel engines offer potential CO<sub>2</sub> emissions reductions compared to gasoline engines because of their much higher compression ratios, high part-load efficiency (no need of throttling) and inherently lean operation (less fuel is used with a given amount of air). Instead of igniting the mixture of fuel and air with a spark, diesels rely on compression alone to ignite the mixture. The fuel in diesel engines is in the form of small droplets that are directly injected into the cylinder and the power output is controlled by the amount of fuel injected. Producing diesel fuel also consumes less energy than making gasoline, so GHG emissions are lower per amount of fuel delivered to the vehicle.

The downside of diesel engines is that they emit higher concentrations of particulate matter (soot) and their NO<sub>x</sub> emissions are difficult to control. Diesel engines are also more costly than gasoline engines of comparable power, because of their higher cylinder pressures and specialized fuel injection equipment. Although using very clean diesel fuel and particle filters can reduce soot to very low levels, reducing NO<sub>x</sub> to the levels required by California regulations remains a challenge. A three-way catalytic converter (TWC), an efficient technology used to control emission of NO<sub>x</sub> (besides carbon monoxide [CO] and hydrocarbon [HC]) from gasoline engines, cannot be used with diesel engines because it requires a perfectly balanced fuel-air mixture (stoichiometric conditions) to operate.

Peter Hofbauer from FEV discussed both the CO<sub>2</sub> emission benefits and the NO<sub>x</sub> and particulate matter control issues of diesel engines in his second

presentation at the symposium. Mike Ruth from Cummins discussed these issues based on work in a research partnership between Cummins and the U.S. Department of Energy. That program's goal is to develop a new clean diesel engine for light duty vehicles, aimed at increasing fuel economy by 50% and reaching the emission levels of particulate matter and NO<sub>x</sub> associated with Tier II regulations. So far they have achieved improvements that translate to CO<sub>2</sub> emission reductions in the order of 30% for both SUVs and pickups. They have met the emission standards for particulate matter but have not been able to meet the NO<sub>x</sub> emission standards even with the use of NO<sub>x</sub> adsorbers.

Joe Kubsh from Manufacturers of Emission Controls Association presented this "NO<sub>x</sub> adsorber" technology that basically controls NO<sub>x</sub> in a two-step process. First, during the diesel engines normal lean-operation mode, NO<sub>x</sub> is stored in the catalyst. Then NO<sub>x</sub> is periodically reduced during short periods of time while the engine is operating under stoichiometric conditions (a precise amount of oxygen to combust the fuel). Although the technology provides low NO<sub>x</sub> emissions levels, there are certain challenges when applied to diesel engines because of the difficulties of operating these engines at stoichiometric air-to-fuel ratios. This technology also requires ultra low levels of sulfur (below 30 ppm) that are now exceeded by most U.S. diesel fuel and may still be exceeded under the new U.S. Tier II regulations.

Kubsh and Matii Maricq (from Research and Advanced Engineering, Ford Motor Company) presented diesel particulate filters (DPF), a technology that controls emission of particulate matter. DPF systems consist of a filter material positioned in the exhaust designed to collect solid and liquid particulate emissions while allowing the exhaust gases to pass through the system (MECA, 2000). High efficiencies for particulate matter control are achieved with these systems, over 85% according to Kubsh and over 99% according to Maricq. But both speakers noted that a particulate filter has to be regenerated to clean the collected particles that fill it up but that current methods of regenerating pose fuel economy penalties.

Mark Jacobson from Stanford University commented on the global warming impacts of particulate matter emission (mostly black carbon and organic matter) from diesel engines. In his opinion the emission of particulate matter from diesel vehicles permitted by U.S. Tier II (0.02 g/mi) and California LEV II (0.01 g/mi) regulations make these engines a greater impact on global warming when compared to SI gasoline engines even though diesel engines have lower CO<sub>2</sub> emissions.

### *Gasoline Direct Injection (GDI)*

Conventional gasoline engines inject fuel into the inlet port before the inlet valve is open to achieve a good homogenous mixture of fuel and air. In a GDI engine, gasoline is directly injected into the cylinder the same way as in a diesel engine. Stephen Brueckner from AVL presented technology development trends for GDI engines.

GDI permits more fine-tuned control of the amount of fuel injected as well as control of injection timing independently from valve timing. GDI engines can reduce CO<sub>2</sub> emissions in a number of ways, including better "breathing"

efficiency, higher compression ratio, the potential for lean operation and reduction of pumping losses. Thus, GDI engines share some of the advantages of diesel engines. If operated lean, however, GDI shares the diesel problems with NOx control.

Brueckner stated that the first generation of GDI engines used a wall-guided system to stratify the charge. Following their introduction by Mitsubishi, these designs were improved to expand their operating range (engine speed and load). However, they reached a limit on their fuel consumption reduction because the use of NOx adsorbers requires that the engine operates in non-lean mode for periods of time. The second generation of GDI engines improved the way fuel is injected, improving the emission controls as well as extending the lean-mode operating range and so yielding greater reductions of fuel consumption.

Brueckner also introduced a different version of GDI that combines the fuel economy benefits of direct injection (with homogeneous charge and stoichiometric conditions) with turbocharging and downsizing. This last alternative has the additional benefit of using conventional three-way catalysts to control NOx emissions because it runs at stoichiometric rather than lean conditions.

Considering the U.S. city driving cycle, these GDI versions offer different fuel economy benefits depending on the size of engine to which they are applied. Brueckner noted that the best choice for a SUV-class vehicle is a second-generation GDI engine. For a small vehicle, the best choice is the turbocharged downsized GDI version. Table 3 provides the range of CO<sub>2</sub> reduction improvements and costs associated with the different GDI technologies as presented by Brueckner. The fairly wide range of CO<sub>2</sub> reductions shown is an example of how the benefits depend on the sophistication of the underlying design to which a new technology is applied.

TABLE 3  
**GDI technologies: their CO<sub>2</sub> reduction potential and cost**

<b>Technology</b>	<b>CO<sub>2</sub> Reduction*</b>	<b>Cost</b>
GDI 1 <sup>st</sup> Generation	5-15%	\$ 400
GDI 2 <sup>nd</sup> Generation	7-20%	\$ 400
GDI Turbocharged Homogeneous	7-20%	\$ 300

Notes: \*Depends on the engine to which the technology is compared.  
Source: Brueckner presentation

Strict emissions regulations and currently low-quality fuel (with high levels of sulfur) inhibit the use of lean-operated GDI in the United States. Therefore, Brueckner sees a turbocharged homogenous version of GDI as being most suitable for the U.S. market.

### *New approaches to internal combustion*

In addition to developing advanced refinements of conventional spark-ignition (gasoline) and compression-ignition (diesel) engines, research is underway on completely new techniques for internal combustion in piston engines. One such approach is Homogeneous Charge Compression Ignition (HCCI), which

promises substantial emissions reductions for diesel-fueled engines. Another new approach is Controlled Auto-Ignition (CAI), which promises throttle-free control and higher cycle efficiency along with extremely low emissions for gasoline-fueled engines.

HCCI can be thought of as an approach that combines features from both traditional gasoline and diesel engines. In HCCI, fuel is homogeneously premixed with air, as in a gasoline spark ignition engine, but with a high air-to-fuel ratio (lean mixture). When the piston reaches its highest point, this lean mixture spontaneously combusts from compression heating, as in a diesel engine. This HCCI autoignition does not pose any knock problems, as with autoignition in SI engines, because the excess air keeps the maximum temperature of the burned gases relatively low.

HCCI generates very little NO<sub>x</sub> due to the low temperatures at which combustion is induced and the high dilution levels that are achievable in the homogeneous charge. Also, because the charge is homogeneous (premixed), HCCI engines produce few particulate (PM) emissions, potentially side-stepping the NO<sub>x</sub>-vs-PM trade-off confronted by conventional diesel engines.

Two problems, however, limit the introduction of HCCI technology despite its advantages:

- HCCI has highly constrained operating ranges where the proper combustion timing can be achieved. Research is underway to extend its range of operations.
- HCCI is prone to HC and CO emissions, requiring the development of new injection systems to minimize this problem or new catalytic converters that can function with the low exhaust temperature.

CAI can be viewed as a revolutionary approach for gasoline combustion in which the use of spark ignition is replaced by using highly precise fuel injection and induction processes to exploit the fuel-air mixtures ability to ignite spontaneously under high pressure. CAI can be made to occur at stoichiometric (chemically exact) conditions and it entails very high levels of exhaust gas recirculation (EGR). Because of the stoichiometric combustion and high exhaust-gas temperature (in contrast to HCCI), a conventional three-way catalyst can be used with CAI to achieve extremely low emissions levels.

During the symposium, Jamie Turner discussed the work on CAI and camless engines that is underway at Lotus Engineering. As noted above under the Variable Valve Control discussion, CAI is being explored as an application of fully-variable camless valve control technology, such as Lotus Active Valve Train (AVT). Turner described the mechanisms and characteristics of CAI, focusing on the fuel consumption and pollutant emission levels that can be expected with the use of the technology. In addition to basic ongoing development needs, a challenge for CAI is that it degrades the smoothness (low NVH) characteristics of gasoline engines. Nevertheless, Lotus analysis suggests that CAI can have fuel economy benefits in the 16% to 32% range, depending on operating conditions, and NO<sub>x</sub> emissions can be as much as 98% lower than in a conventional SI engine. HC emissions can be higher or lower than in a conventional SI engine.

depending on the operating conditions. Therefore, a catalytic converter is needed for cleanup.

### *Integrated Starter-Generator*

An ISG is a system that replaces both the current starter motor and the alternator. With the aid of this system the engine can be shut off during idling conditions (e.g., when sitting in traffic or at a stoplight) and then automatically start up and move as soon as the gas pedal is pressed. Neville Jackson of Ricardo presented an ISG technology called "i-MoGen" (intelligent Motor Generator) being developed in a joint program between Ricardo and Valeo for application to a downsized turbocharged diesel engine.

In addition to fuel savings from idle-off, ISG systems offer several other efficiency benefits:

- Higher electrical efficiency over a broader load range, reducing the drain on the engine for servicing electrical loads.
- The potential for upgrading the vehicle electrical system from 12 volts to 42 volts, enabling the conversion of most accessories (including power steering and air conditioning) to electric drive, providing better control and saving fuel by avoiding belt drives that tax the engine even when the devices are not needed.
- The ISG might also enable a degree of regenerative braking and provide an evolutionary manufacturing and market path toward mild levels of hybrid propulsion.

According to Jackson, the i-MoGen 42-volt ISG system has demonstrated an 8% reduction in fuel consumption when applied to a given engine. A 20% reduction in fuel consumption was achieved by downsizing the engine, and incorporating a fast warm-up and intelligent cooling system. Also the electrical assistance that the ISG/42 volt system provides has been used to improve the performance of turbocharged engines at low speeds, making for a good match between these two technologies.

### *Hybrid Electric Vehicles*

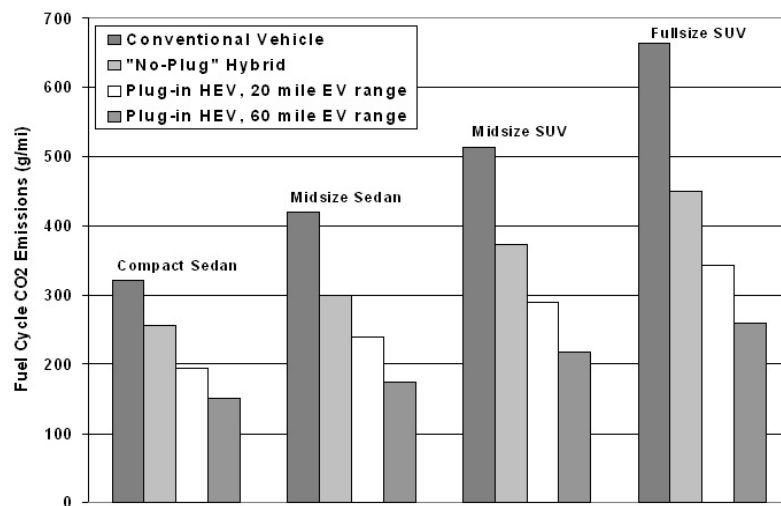
A HEV combines a combustion engine with an electric motor and generator plus an energy storage device. The motor and generator can be a single device that performs both functions, or more than one such device can be used depending on the design. To date HEVs have used batteries as the energy storage device, but an ultracapacitor can be used instead of, or in addition to, a battery. HEVs can reduce fuel consumption by enabling the combustion engine to operate more efficiently, by using a smaller engine as the electric motor can meet peak power needs and by recovering energy during braking that otherwise would be wasted.

To date, three HEV vehicles have been available in the U.S. market: the Toyota Prius, the Honda Insight and the Honda Civic Hybrid. Dave Hermance of Toyota and Ben Knight from Honda presented the major features of these

vehicles. According to Hermance and Knight, the Prius and Civic Hybrid achieve combined fuel economies on the order of 48 mpg. This level is 75% higher than the 2002 compact car class average of 27.2 mpg.<sup>12</sup> In the Civic Hybrid and Prius, some of the improvements come from hybridization but some come from a better transmission (e.g., a CVT), more efficient engines and other features. Although having better efficiencies and achieving good performance and low emission levels, HEVs face a price premium of roughly \$3,500 compared to similar vehicles. This is the main limitation that inhibits greater market penetration of HEVs according to Hermance and Knight.

Prof. Andy Frank from UC Davis presented a different configuration of HEV that incorporates higher electrical power and battery capacities, allowing a significant zero-emission (all electrical) driving range. This "plug-in hybrid" configuration uses smaller combustion engines but bigger battery packs that need to be recharged with grid electricity. Increasing the electric range of the vehicle reduces CO<sub>2</sub> emission as can be seen in Figure 6. However, increasing the electrical system capacity of the HEVs also increases the price. For example the cost premium of a hybrid vehicles having a 60 mile all-electric range is around \$8,000, according to Frank.

FIGURE 6  
CO<sub>2</sub> emissions from different HEV configurations



Source: Frank presentation

#### VEHICLE LOAD REDUCTION

Besides improving the efficiency with which the powertrain converts fuel to useful energy, several approaches can be incorporated into vehicle platforms that

<sup>12</sup> Hellman and Heavenrich (2003), Table G-5. Caution is needed when interpreting such comparisons because EPA's compact class includes a diversity of vehicles including luxury, sporty and performance models to which the Civic and Prius may not be directly comparable.

reduce the required energy to move a car or truck in the first place. Options include reducing vehicle mass without making the vehicle smaller, reducing aerodynamic drag and reducing tire rolling resistance. Improving the efficiency of vehicle accessories can also result in lower CO<sub>2</sub> emissions. Of course, making vehicles smaller lowers fuel consumption, but can also reduce utility so this method is generally excluded from assessments focusing on technology-based approaches to emissions reduction. Several strategies for mass reduction without downsizing were addressed at the symposium.

### *Mass reduction*

The vehicle mass directly affects the energy requirement to move a vehicle. Mass reduction, without reducing vehicle size or utility, can offer substantial reductions in fuel consumption and CO<sub>2</sub> emissions, both directly and through indirect effects of enabling a smaller powertrain and reducing tire rolling losses (which depend on both the composition and design of the tires, and the weight they have to carry).

Prof. Marc Ross from the University of Michigan discussed weight reduction strategies to reduce fuel consumption. According to Dr. Ross, mass reduction can also decrease traffic fatalities if pursued through a carefully implemented strategy. These conclusions were reached by a study that analyzed the combined risk performance (both risk to drivers and risk to occupants of other vehicles) of different classes of vehicles.

Three kinds of changes could be made to reduce the mass of heavier vehicles (such as SUVs), improving their fuel efficiency and also decreasing the potential of fatality risks:

- SUV designs could be shifted from truck-based to car-based (as in crossover designs), resulting in greater crash compatibility and mass reduction. A softer and lower front would also be adopted for pickups, albeit with less opportunity for mass reduction.
- The use of lightweight materials, such as higher strength steels, aluminum and engineering plastics, could be increased.
- High-efficiency propulsion systems, which are also lighter in weight, could be adopted. Important examples are small engines with high specific power, and automatic transmissions without a torque converter (using motorized clutches and sophisticated controls to assure smooth shifting).

### **Simulation of aggregated technologies**

The individual technologies presented in many symposium sessions can be jointly implemented to achieve total CO<sub>2</sub> emission reductions that reflect synergistic interactions (both positive and negative). System analysis tools can assess the total reduction potential without the need of building actual prototype vehicles. These tools can simulate vehicle subsystems in a holistic way, assessing the performance of the vehicle according to different criteria such as: performance;

fuel consumption; noise and air pollutant emissions; initial cost; reliability and durability; maintenance requirements; and how these factors affect system availability and operating costs. Some of these criteria conflict with each other, so the systems analysis process can also reflect design trade-offs that have to be considered when assessing the practical CO<sub>2</sub> emissions reduction potential.

Peter Hofbauer from FEV gave an overview of how system analysis has been used to assess these trade-offs that confront vehicle designers.

Albert Turtcher of AVL presented the modeling tools that his firm offers to perform such system analysis. According to their simulations, Turtcher reported that internal combustion engines still have a potential fuel consumption reduction of 20% to 30%. For example, a downsized engine with an integrated starter generator and improved auto transmission shows the potential to achieve CO<sub>2</sub> emission in the range of 90-120 g/km for the European driving cycle (in comparison to the EU voluntary target of 140 g/km for 2008).

Neville Jackson presented the modeling software offered by Ricardo, focusing on the improvements that can be achieved in the emission control system with the aid of these tools.

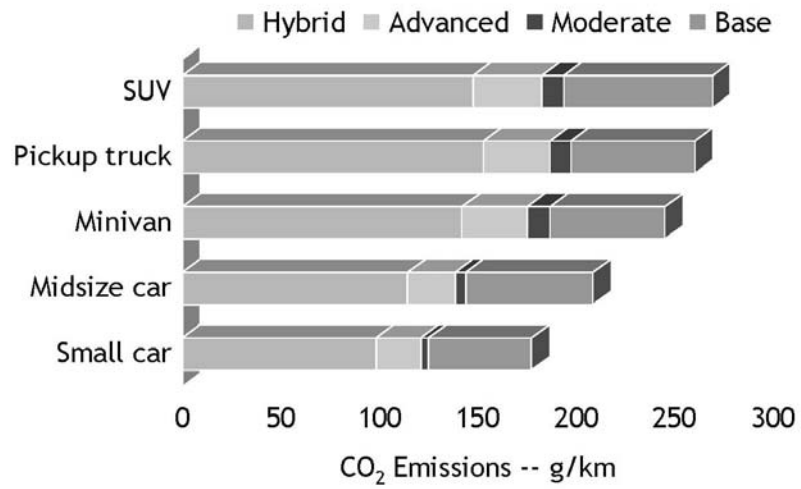
TABLE 4  
**System analysis results: overview of potential fleet average CO<sub>2</sub> emission rates**

<b>Case</b>	<b>g/km</b>	<b>Reduction</b>
Baseline (MY 2000)	228	--
Packages without mass reduction		
Moderate	168	26%
Advanced	160	30%
Hybrid	130	43%
Packages with mass reduction		
Moderate	155	32%
Advanced	134	41%
Hybrid	109	52%

Source: DeCicco presentation

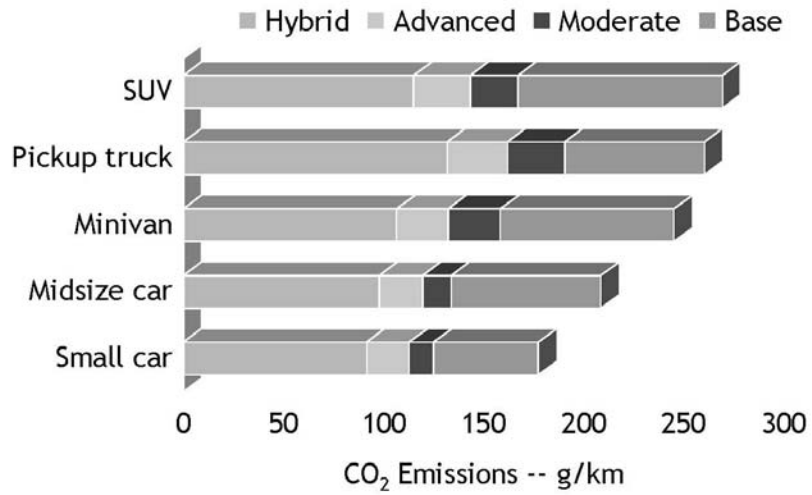
John DeCicco from Environmental Defense presented the results he and his colleagues developed by simulating several technology packages that could be applied to major classes of vehicles in order to reduce CO<sub>2</sub> emissions. According to his results, summarized in Figures 7 and 8, optimal application of available technologies can reduce CO<sub>2</sub> emissions per vehicle by as much as 50% depending on the type of vehicle and degree of advancement applied. He also presented cost estimates based on national-scale production, amounting to vehicle price impacts well under 10%, but cautioned that new analyses are needed to estimate costs for state-level production scales.

FIGURE 7  
**System analysis results for representative models, without mass reduction**



Source: DeCicco presentation

FIGURE 8  
**System analysis results for representative models, with mass reduction**



Source: DeCicco presentation

## Alternative Fuel Vehicles

CO<sub>2</sub> emissions from vehicles are dependent not only on the amount of fuel that is being used but also on the type of fuel. Using fuels with lower carbon intensity (i.e. less carbon emitted per unit of energy content in the fuel) also reduces CO<sub>2</sub> emissions. Nearly all motor vehicles today are powered by either gasoline or diesel (both petroleum products). Examples of fuels with potentially lower carbon intensity than gasoline or diesel are alcohol fuels (methanol and ethanol), natural gas (either compressed or liquefied) or hydrogen. The actual GHG emissions impact of a fuel depends on emissions throughout the whole chain of its production, distribution, and use—what is termed the "full fuel cycle." Such full fuel cycle (so-called "well-to-wheels") analysis is needed to properly estimate the GHG emissions impacts of alternative fuels.

C.E. Thomas from H<sub>2</sub>Gen Innovations, inc., presented one such well-to-wheel analysis in which he compared the two different hydrogen technologies (fuel cells vehicles and internal combustion hydrogen vehicles) with conventional gasoline vehicles and HEVs. His analysis considered how different technology paths would play out over the next 100 years, as illustrated in Figure 9. Thomas assumes that hydrogen production becomes increasingly more renewable over the years. With these assumptions his analysis demonstrated that, on a 100-year basis, hydrogen vehicles, either fuel cells or internal combustion engines, emit much less GHG than conventional and HEV gasoline vehicles. The main issue would be the extra costs of the hydrogen technologies. Table 5 provides Thomas' detailed results.

TABLE 5  
**Incremental vehicle costs and GHG emissions associated with different vehicle technologies**

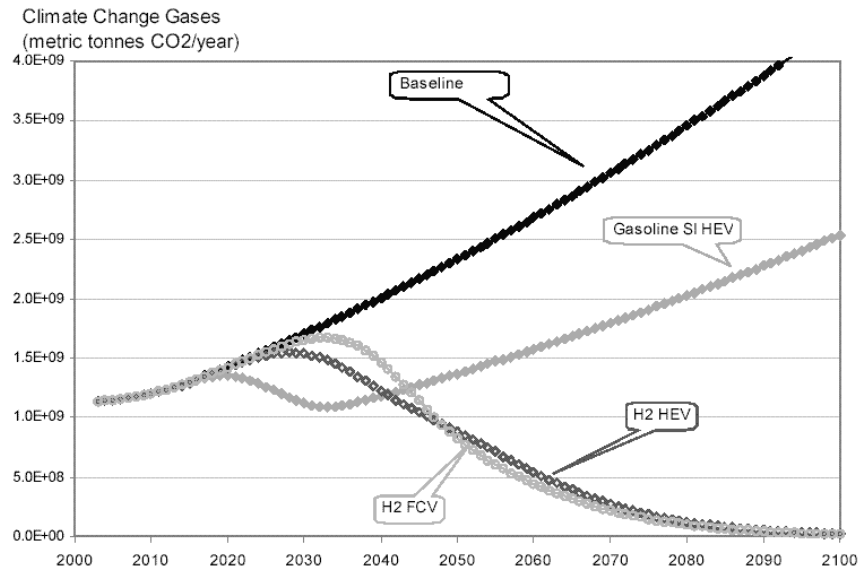
	<b>Greenhouse Gases (grams/mile)</b>	<b>Current Incremental Vehicle Cost</b>	<b>Future Incremental Vehicle Cost in Mass Production</b>
Gasoline ICEV	401	0	0
Gasoline SI HEV	287	\$12,300	\$650
Hydrogen HEV	313 (0)*	\$17,800	\$1,830
Hydrogen FCV	246 (0)*	\$300,000 or more	\$2,300

ICEV = Internal Combustion Engine Vehicle; HEV = Hybrid Electric Vehicle; SI = Spark-ignition; FCV = Fuel Cell Vehicle.

\*Estimates for hydrogen vehicles assume natural gas feedstock; the zero values in parenthesis assume hydrogen from renewable resources emitting no net GHG throughout the fuel cycle.

Source: Thomas presentation

FIGURE 9  
**CO<sub>2</sub> emissions over a 100-year period for different vehicle technology paths**



Source: Thomas presentation

Louis Browning from ICF Consulting and Michael Jackson from TIAX also presented well-to-wheel analysis of alternative fuels and vehicle technologies, but they included broader categories of fuels and vehicle technologies. Their results were largely similar; the differences were associated with the particular assumptions each analyst used (especially the assumptions made for the hydrogen production). Their results are summarized in Table 6 (Browning presented scenarios for two future years, 2010 and 2025). These projections show that advanced gasoline engine technologies (HEV) can reduce GHG in the order of 30% to 40%. Further reductions can be achieved with plug-in HEVs utilizing zero-net-GHG electricity or with alternative fuels (ethanol, methanol, hydrogen) derived from low- or zero-net GHG renewable resources.

TABLE 6  
**Well-to-wheel GHG emissions (gCO<sub>2</sub>equivalent/mile)**

Technology/Fuel	Browning <sup>a</sup>		
	2010	2025	Jackson
CV RFG	420	375	400
HEV RFG	300	250	240
PHEV RF	200	180	0 <sup>b</sup> -230
CV Diesel	360	320	260
CV GDI	NA	320	NA
CV CNG	400	NA	280
CV Ethanol	0-50 <sup>c</sup>	0-50 <sup>c</sup>	250 <sup>d</sup>
CV Methanol	-260 <sup>e</sup> -20 <sup>f</sup>	-260 <sup>e</sup> -20 <sup>f</sup>	NA
H <sub>2</sub> FCV NG onsite	NA	175	180
H <sub>2</sub> FCV electrolysis	NA	250 <sup>g</sup>	100 <sup>h</sup> -400 <sup>g</sup>

Estimates assume a CAFE driving mix. CV = Conventional Vehicle (internal combustion engine); RFG = California Reformulated Gasoline; HEV = Hybrid Electric Vehicle; PHEV = Plug-in Hybrid Electric Vehicle; GDI = Gasoline Direct Injection; CNG = Compressed Natural Gas. NG onsite assumes hydrogen reformed from natural gas onsite at fueling stations.

Notes: <sup>a</sup> Results given for Browning are for two future year scenarios; no specification was made for methanol and ethanol fuels; <sup>b</sup> Emission is 0 for renewable electricity generation; <sup>c</sup> Assumes renewable woody or herbaceous biomass for ethanol production; <sup>d</sup> Ethanol is E85 produced from corn and blended with 15% gasoline; <sup>e</sup> Assumes methanol from landfill gas; <sup>f</sup> Assumes methanol from non-American flared gas; <sup>g</sup> Assumes combined cycle natural gas electricity generation; <sup>h</sup> Assumes renewable electricity generation.

Source: Browning presentation; Jackson presentation

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## Appendix A. Symposium presentations

Available on the web at: [www.arb.ca.gov/gcc/techsem/symposium.htm](http://www.arb.ca.gov/gcc/techsem/symposium.htm)

### Session I: Reducing HFCs

James A. Baker, Delphi Corporation  
Greenhouse Gas Emissions From Vehicle Air Conditioning Systems  
Ward Atkinson, Sun Test Engineering  
Overview of Mobile Air Conditioning Testing and Evaluation

### Session II: Aftertreatment Technology for Reducing Black Carbon, N<sub>2</sub>O and CH<sub>4</sub>

Professor Mark Jacobson, Stanford University  
Global Warming Impact of Black Carbon  
Matti Maricq, Ph.D., Ford Research and Advanced Engineering  
Future Technology Diesel: Reducing Black Carbon Emissions  
Joe Kubsh, Ph.D., Manufacturers of Emission Controls Association  
Controlling Particulate Emissions From Light Duty Vehicles  
Alex Lawson, Ph.D., Teleflex GFI Control Systems LP  
Methods to Reduce Methane Emissions

### Session III: Reducing CO<sub>2</sub> Emissions /Powertrain and Drivetrain Modifications

Loren Beard, DaimlerChrysler  
Internal Combustion Engine Improvements  
Professor Marc Ross, University of Michigan  
Low Cost and Near Term Greenhouse Gas Emission Reduction  
Dr. Peter Hofbauer, FEV  
Variable Valve Actuation: New Issues, Solutions and Technology  
Roland Kemmler, DaimlerChrysler  
Cylinder Deactivation  
Dr. S. M. Shahed, Garrett  
Gasoline Engine Downsizing and Boosting  
Herbert Mozer, ZF Group  
Automatic Transmission Development and Contributions  
Mike Ruth, Cummins  
Clean Diesel Program  
Neville Jackson, Ricardo, Inc.  
i-Mo-Gen; Integrated Starter/Generator Technology  
Jamie Turner, Lotus  
Controlled Auto Ignition and Camless Engines  
Stephen Brueckner, AVL  
Gasoline Direct Injection Technologies

## **Session IV: Hybrid Electric and Alternative Fuel Vehicles**

Ben Knight, Honda

Honda's Perspective on Hybrid Electric Vehicles

Dave Hermance, Toyota

Toyota's Hybrids

Dr. Andy Frank, UC Davis

Advanced Hybrid Technology

Dr. Sandy Thomas, H2Gen Innovations

Hydrogen Fuel Cell Vehicles vs. Hybrid Electric Vehicles

Dr. Louis Browning, ICF Consulting

The Role of Alternative Fuels in Reducing Greenhouse Gases

Michael Jackson, TIAX

Well-to-Wheels Analysis of Alternative Fuels

## **Session V: Simulation of Aggregated Technologies**

Albert Turtscher, AVL

Advanced Simulation Technologies

John DeCicco, Environmental Defense

Systems Analysis of Low CO<sub>2</sub> Emission Designs

Neville Jackson, Ricardo, Inc.

Systems Analysis for Configuration and Control Optimization

Dr. Peter Hofbauer, FEV

Systems Analysis: Engines in Compact Cars and Advanced Diesels

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## Acronyms

A/C	air conditioning (automotive)
AVT	active valve timing
CAI	controlled auto-ignition
CARB	California Air Resources Board
CEC	California Energy Commission
CFC	chlorofluorocarbon
CH <sub>4</sub>	methane
CO <sub>2</sub>	carbon dioxide
CO <sub>2</sub> eq	carbon dioxide equivalent
CVT	continuously variable transmission
DPF	diesel particulate filter
EGR	exhaust gas recirculation
EMVT	electromechanical valve train
GDI	gasoline direct injection
GHG	greenhouse gas
GWP	global warming potential
HC	hydrocarbon
HCCI	homogeneous charge compression ignition
HEV	hybrid electric vehicle
HFC	hydrofluorocarbon
ISG	integrated starter-generator
LEV	low emission vehicle
MECA	Manufacturers of Emission Controls Association
N <sub>2</sub> O	nitrous oxide
NVH	noise, vibration and harshness
PM	particulate matter
SI	spark ignition
TWC	three-way catalyst
VVC	variable valve control
VVT	variable valve timing

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