Climate Control

Global Warming Solutions *for* California Cars

Union of Concerned Scientists
Citizens and Scientists for Environmental Solutions

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Union of Concerned Scientists
April 2004

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The Union of Concerned Scientists is a nonprofit partnership of scientists and citizens combining rigorous scientific analysis, innovative policy development, and effective citizen advocacy to achieve practical environmental solutions.

The Union of Concerned Scientists Clean Vehicles Program develops and promotes strategies to reduce the adverse environmental impact of the U.S. transportation system.

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Two Brattle Square
Cambridge, MA 02238-9105

Or, email *pubs@ucsusa.org* or call (617) 547-5552.

Design: Catalano Design
Printed on recycled paper

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Acknowledgments

Support for this work was provided by The Energy Foundation, Foundation M, The J.M. Kaplan Fund, Martin Fabert Foundation, Oak Foundation, Tides Foundation/Mendel McCormack Fund, Steven and Michele Kirsch Foundation, V. Kann Rasmussen Foundation, Wallace Global Fund, and The William and Flora Hewlett Foundation.

The author is particularly indebted to Feng An and David Friedman for their expertise and collaboration on the modeling analysis that provides the foundation of this report. Thanks also to Marc Ross and John DeCicco who provided valuable input to the modeling process.

The author thanks Michael Walsh, Roland Hwang, John DeCicco, Kathryn Phillips, Wendy James, Jamie Knapp, Eric Haxthausen, and Mary Jean Burer for helpful comments on drafts of this report. Thanks also to Jason Mark for his advice and guidance throughout the process of developing the report.

Thanks to Bryan Wadsworth for his patient editing and overseeing the production of this report.

The opinions expressed in this report do not necessarily represent the opinions of the foundations that supported the work or the individuals who reviewed and commented on it. The opinions and information contained herein are the sole responsibility of the author.

EXECUTIVE SUMMARY

Global warming is the most serious long-term environmental threat facing California, the nation, and the world. An international scientific consensus predicts that the average global temperature will increase during the coming century and the resulting changes will have a substantial impact on global weather patterns.

Global Warming Will Affect California

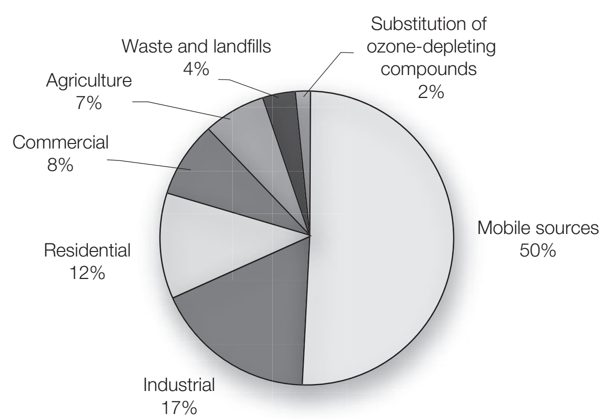
While atmospheric changes are occurring on a global scale, the effect of these changes will be felt locally. Even an increase of a few degrees can affect the weather patterns seen across California, affecting snowpack amounts and, in turn, water supplies. In addition, increases in average temperatures could also lead to the loss of native species and vegetation, damage to agricultural crops, unhealthy air quality, increased spread of infectious diseases, and increases in the frequency and severity of storms and natural disasters such as wildfires and mudslides. All of these factors increase the risks to California's public health, natural resources, and infrastructure. Responding to and mitigating these risks will place large demands on the state's economy throughout this century.

Because the federal government has failed to take action against climate change, the states have begun to take up the burden of reducing emissions of heat-trapping gases—the pollutants that contribute to global warming. California, as it has in the past, is leading the way by focusing on the largest source of heat-trapping emissions in the state: motor vehicles. The 2002 passage of A.B. 1493, also known as the California Vehicle Global Warming Law, made the Golden State's government the first in the world to require limits on heat-trapping emissions from passenger vehicles.

Stopping the Problem at Its Source

More than 1.5 million new vehicles are sold each year in California. As a result of the state's aggressive air quality regulations, these vehicles have a much smaller impact on local air quality than they did 20 years ago, but their emissions of heat-trapping gases have continued to increase. Mobile sources including passenger vehicles account for approximately half of California's global warming pollution.

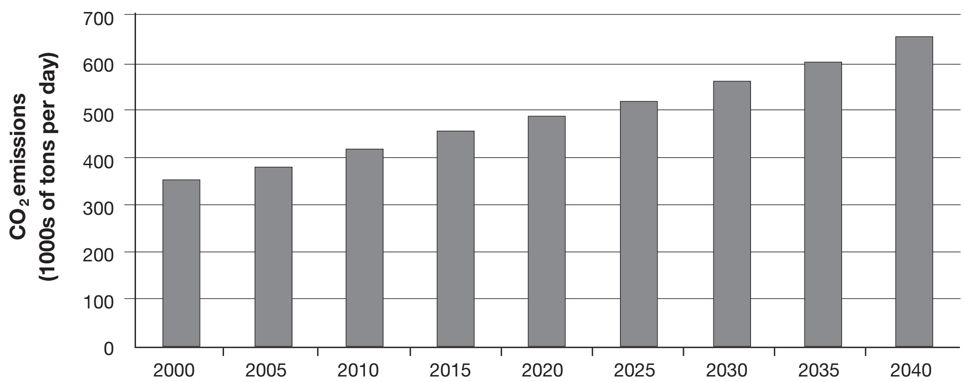
Figure ES-1: **Heat-Trapping Gas Emissions in California by Source**



NOTE: Does not include emissions from out-of-state electricity generation.
SOURCE: CEC, 2002.

Overall, the combustion of gasoline by motor vehicles is responsible for almost 40 percent of the state's carbon dioxide (CO_2) emission inventory and slightly more than 30 percent of its total

Figure ES-2: CO_2 Emissions from Passenger Vehicles



SOURCE: EMFAC 2002 (CARB, no date).

heat-trapping emission inventory. A model year 2000 vehicle sold in California will emit about 90 tons of heat-trapping gases from its tailpipe—more than 95 percent of which take the form of CO_2—into the atmosphere during its lifetime. Without action to reduce these emissions, the total CO_2 produced by the state's passenger vehicle fleet will almost double by 2040.

Emission Reductions Are Possible Today

Enormous potential exists to reduce the global warming impact of new vehicles sold in California. Improvements in air conditioning systems, engines, and transmissions, as well as reductions in vehicle loads, are possible with technologies available today. These technologies could begin producing substantial emission reductions immediately if automakers decided to apply them fleetwide. Even greater reductions are possible with technologies that will be introduced over the next five years.

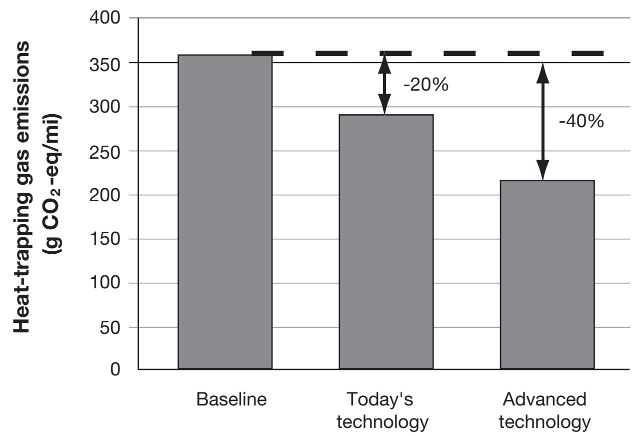
Emission-reducing technologies that are currently available and already being used in specific vehicles include variable valve lift and timing (in many Honda models), continuously variable transmissions (in the Saturn Ion, Nissan Murano, and Mini Cooper), and cylinder deactivation (which General Motors is planning to use in many of its large trucks beginning in 2004). These examples, while demonstrating the viability and consumer acceptance of such technologies, are the exceptions rather than the rule. Further penetration of these technologies into the new vehicle fleet could lead to greater near-term emission reductions, but, as history has shown, most automakers will not fulfill this technological potential on their own.

The modeling conducted by the Union of Concerned Scientists in this report shows that by applying currently available technology to all new vehicles sold in California, fleet average heat-trapping emissions could be reduced 20 percent. Emissions from a Ford Explorer could be reduced nearly 25 percent, and emissions from a Toyota Camry could be reduced almost 20 percent. Similar reductions are possible in all vehicle classes. Furthermore, the additional cost of these vehicle improvements would be recouped in the form of decreased operating costs after less than three and a half years of driving, on average.

Realizing the potential of today's technology is just the first step down a path to vehicles that are both consumer- and climate-friendly. Many new technologies that could lead to even greater emission reductions are just on the horizon, including stoichiometric direct-injection engines, automated manual transmissions, and 42V integrated starter-generators that allow the engine to turn off while idling.

Our modeling shows that these technologies, which should be available for fleetwide implementation during the next five years, could deliver a 40 percent reduction in fleet average heat-trapping emissions when combined with currently available technologies. For example, a Ford Explorer could achieve a 43 percent reduction in emissions and a Toyota Camry could achieve a 41 percent reduction. The additional cost associated with these vehicle improvements could be recouped in less than four and a half years of driving, on average. But society cannot benefit from these technologies unless automakers actually install them.

Figure ES-3: **Emission Reduction Potential for the California New Vehicle Fleet**



NOTE: Estimates based on UCS modeling.

The improvements described above are not limited to the Ford Explorer and Toyota Camry. As shown in Table ES-1, tremendous potential for emission reductions exists across the entire vehicle fleet, both with technologies available today and those emerging over the coming years.

Table ES-1: **Emission Reduction Potential Across the California Vehicle Fleet**

		Small Car	Large Car	Minivan	SUV	Pickup	Fleet Average
		Ford Focus	Toyota Camry	Dodge Grand Caravan	Ford Explorer	Chevrolet Silverado 1500 (extended cab)	
Baseline	Heat-trapping gas emissions ($g\ CO_2$-eq/mi)	292.9	334.2	368.6	440.0	487.1	361.3
Today's Technology	Heat-trapping gas emissions ($g\ CO_2$-eq/mi)	240.6	270.8	303.3	333.7	383.2	289.3
	% improvement	18%	19%	18%	24%	21%	20%
	Cost of improvement	$495	$620	$620	$620	$700	$590
	Payback time (years)	3.8	3.9	3.8	1.9	2.3	3.2
Advanced Technology	Heat-trapping gas emissions ($g\ CO_2$-eq/mi)	178.3	196.8	234.7	251.3	297.3	216.9
	% improvement	39%	41%	36%	43%	39%	40%
	Cost of improvement	$1,710	$1,960	$1,960	$1,960	$2,135	$1,904
	Payback time (years)	5.2	4.8	5.1	3.2	3.5	4.4

In addition to their environmental benefits, these improvements can provide California consumers with savings resulting from reduced operating costs. A new vehicle fleet that realizes a 20 percent reduction in fleet average heat-trapping emissions, for example, could save California drivers as a whole more than $2 billion over the life of their vehicles. A 40 percent reduction could save California consumers more than $4 billion.

California's Actions Can Have a Global Impact

Because California accounts for more than 10 percent of all new vehicles sold in the United States, reducing emissions of heat-trapping gases here will have a noticeable effect on the national inventory. Furthermore, the way in which the state regulates its motor vehicles also has a powerful influence on the rest of the nation.

Several states have already adopted California's emission regulations for passenger vehicles and, as a result, passenger vehicles that meet current California emission standards now account for approximately one-quarter of new U.S. vehicle sales. Adding the regulations outlined in California's new Vehicle Global Warming Law to these standards would produce even larger reductions in the national heat-trapping emission inventory.

A number of states have also entered into agreements to take regional actions limiting heat-trapping emissions. If all of the states that have undertaken significant global warming initiatives to date were to adopt California vehicle tailpipe standards, including those set by the California Vehicle Global Warming Law, roughly one-third of the new vehicles sold in this country would be helping to lower global warming emissions.

The impact of California's regulations is not even confined to our national borders. Canada, too, has already expressed a desire to adopt regulations similar to those of California if it is unable to reach a voluntary agreement with automakers. Adoption of California-style standards in Canada would affect more than a million more new vehicles each year.

Chapter 1
Introduction

Global warming is the most serious long-term environmental threat facing California, the nation, and the world. Concentrations of heat-trapping gases in the atmosphere have increased dramatically since the start of the Industrial Revolution, largely as the result of human activity (especially the burning of fossil fuels). This build-up, according to an international scientific consensus, is changing the global climate in terms of temperature, precipitation patterns, sea level, and the occurrence of extreme events (IPCC, 2001; Schneider and Sarukhan, 2001; Field et al., 1999).

International negotiations and treaties to reduce heat-trapping emissions exist, but the United States government has refused to commit itself to any such agreement. Despite this lack of federal action on global warming, some important regulatory action has been taking place at the state level (Rabe, 2003). In 2002, for example, California took the most aggressive step of any state to limit heat-trapping emissions by passing A.B. 1493 (also known as the California Vehicle Global Warming Law), which requires the California Air Resources Board (CARB) to set regulations limiting the emissions of heat-trapping gases from passenger vehicles.

Global Warming's Impact on California

While the effects of increased heat-trapping gas concentrations are often observed on a global scale, climate change will also have direct and noticeable effects on the state of California—some of which are already being seen. Sea level rise has been observed in San Francisco Bay, and spring flow from watersheds in the Sierra Nevada Mountains is coming earlier in the calendar year (CEC, 2003b). Warming observed in the California Current has coincided with a decline in zooplankton and seabird populations (Field et al., 1999).

More severe impacts are likely over the coming century. Increases in annual average temperatures, for example, will cause a number of changes in California's weather patterns, environment, and species (as depicted in Table 1-1).

Table 1-1: **Likely Impact of Global Warming on California**

Precipitation Changes
Less snowpack in Sierra Nevada, leading to reduction in summer stream flow and water supply
Increased winter rains, leading to greater flood and landslide risks
Extreme Weather
Warmer winters and summers
Increased frequency and severity of events such as El Niño
More severe and prolonged droughts
Habitat and Species Loss
Expanding grasslands
Loss of suitability for agricultural crops
Species extinction
Sea Level Rise

SOURCE: Field et al., 1999.

These changes will, in turn, affect the state's public health and economy. Increased summer temperatures will contribute to increases in ground-level ozone (Taha, 2001). Changes in precipitation patterns and temperature will aid the spread of vector-borne illnesses such as West Nile virus and hantavirus (CEC, 2003b; Field et al., 1999).

Global warming's impact on the state's water supply poses a particularly difficult challenge. Increases in the average temperature will affect the timing of precipitation and likely reduce snowpack levels in the Sierra Nevada Mountains, leading to reduced summer stream flow and a loss of wildlife and habitats dependent on that flow. Declining water supplies will exacerbate the already contentious battle over water between the state's urban, industrial, and agricultural users (Field et al., 1999). And, changes in precipitation patterns will also increase the risk of severe natural disasters such as wildfires, landslides, and floods.

A History of Environmental Leadership

For the past 30 years, California has faced the most serious air quality problems in the country, and the state has emerged as a national leader in the development of air pollution control regulations. It was the first state to set emission standards for motor vehicles, and its regulations have gone on to serve as a model for similar programs around the country. The fact that California's air quality has improved while its vehicle population and vehicle miles traveled have continued to increase demonstrates that the state's air pollution control regulations can successfully deliver environmental benefits without constraining the vehicle market. In fact, automakers have consistently responded to the state's regulations by delivering air quality benefits at costs far below those initially anticipated.

California's leadership extends beyond transportation and air quality. The state has also taken a leading role in the control of heat-trapping emissions by making an enormous commitment to the development of clean, renewable sources of electricity. Its renewable electricity standard will create the largest market for clean energy in the country, and no other state has pledged as many dollars to renewable electricity development (Deyette et al., 2003). California also recently entered into an agreement with Oregon and Washington to reduce heat-trapping emissions on a regional scale.

Furthermore, California took an unprecedented step to limit heat-trapping emissions when Governor Gray Davis signed landmark legislation in July 2002 requiring CARB to establish regulations limiting the heat-trapping gases emitted by new motor vehicles sold in the state.[1] These standards will take effect in January 2006 for model year (MY) 2009 vehicles and later.

The European Union has entered into voluntary agreements with automakers to achieve substantial heat-trapping emission reductions and Canada is working toward a voluntary agreement as well. But the California Vehicle Global Warming Law is the first in the world to require such reductions from vehicles. Like other California regulations in the past, this law will create a standard that serves as a model for other states and countries wanting to control heat-trapping emissions from their passenger vehicle fleets.

Residents of California, like their government, have long demonstrated a concern for the environment. In particular, residents have expressed their desire for vehicles that have less of an impact on the environment. In 2003, 65 percent of Californians indicated they would like to see tougher air pollution standards for new cars, even if those cars are more expensive. And, over the past three years, Californians have expressed increasing concern that action needs to be taken to mitigate the potential impact of global warming (Baldassare, 2000; 2002; 2003). Eighty percent, in fact, support legislation to limit heat-trapping emissions from motor vehicles (Baldassare, 2003).

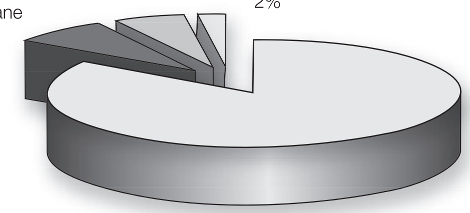
[1]Vehicles subject to these regulations include passenger cars and light-duty trucks whose primary use is non-commercial.

Table 1-2: **Global Warming Potential (GWP) of Heat-Trapping Gases**

Heat-Trapping Gas	GWP
CO_2	1
CH_4	21
N_2O	310
HFC-134a	1,300

SOURCE: IPCC, 2001.

Figure 1-1: **Emissions of Heat-Trapping Gases in California (1999)**



SOURCE: CEC, 2002.

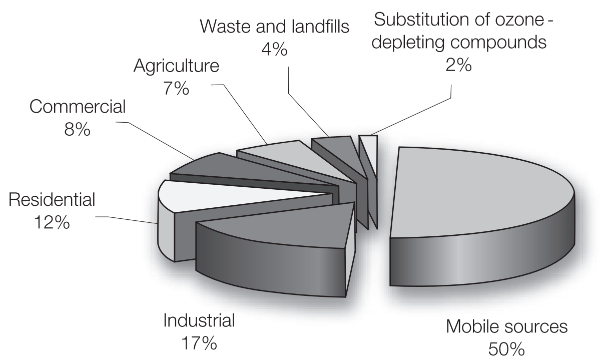
Heat-Trapping Emissions in California

Not all heat-trapping gases are created equal—some absorb more heat than others and have a greater impact on the heat absorbed by the atmosphere, also known as radiative forcing. The potency of a heat-trapping gas, relative to carbon dioxide (CO_2) on a mass basis, is represented by its global warming potential (GWP); Table 1-2 shows the GWP of the most abundant heat-trapping gases emitted by motor vehicles. A higher GWP indicates that the given gas will have a larger effect on climate, per unit mass, than a gas with a lower GWP. So, for example, vehicles may emit HFC-134a in small quantities on a gram-per-mile basis, but those emissions will have a significant impact on the climate as a result of HFC-134a's high GWP.

Mobile sources that burn diesel fuel are major sources of black carbon, which also has a warming effect in the atmosphere (GAO, 2003; Jacobson, 2002). However, the magnitude of this effect is still uncertain and no GWP has yet been defined for black carbon (IPCC, 2001).

Despite having the fourth lowest per capita emissions rate in the country, California is the second largest contributor to the national heat-trapping emission inventory (CEC, 2002). In 1999, California's gross heat-trapping emissions (not including sinks) amounted to 427.7 million metric tons of carbon dioxide equivalent (CO_2-eq). As shown in Figure 1-1, 84 percent of these emissions consisted of actual CO_2. Methane (CH_4), at seven percent, and nitrous oxide (N_2O), at six percent, are the next most abundant heat-trapping gases emitted. As a group, hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6) account for two percent of the statewide inventory.

Figure 1-2: **Heat-Trapping Emissions by Sector (1999)**



NOTE: Does not include emissions generated by imported electricity.
SOURCE: CEC, 2002.

Approximately 60 percent of in-state CO_2 emissions result from the combustion of fossil fuels by mobile sources. Mobile sources are responsible for half of the statewide heat-trapping emissions inventory, as shown in Figure 1-2 (CEC, 2002).

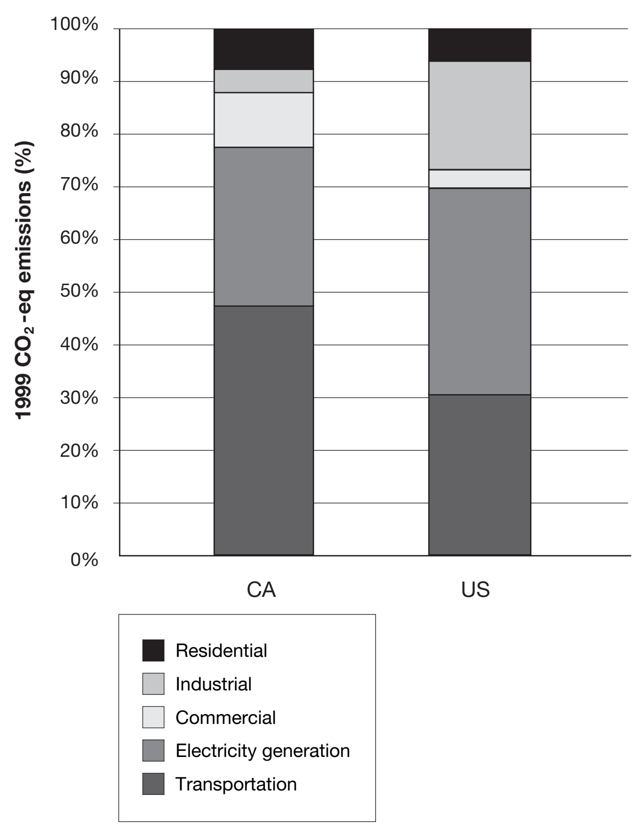
Overall, fossil fuel combustion is the primary source of CO_2 emissions in California and the nation as a whole, but California differs substantially from the rest of the nation in its use of fossil fuels (CEC, 2002). California uses less fossil fuel for heating and electricity generation and more for transportation. The state's reliance on natural gas for electricity generation (rather than coal or fuel oil) reduces its contribution of heat-trapping emissions from that sector. And its mild climate means less energy is dedicated to space heating and cooling than in the rest of the country. As a result, as Figure 1-3 shows, a much larger percentage of CO_2 emissions in California derives from mobile sources than in the country as a whole.

The importance of passenger vehicles in California's heat-trapping emissions inventory is unlikely to decrease in the absence of government regulations. On the contrary, the state's vehicle population and vehicle miles traveled are increasing at a rapid pace. Without action to reduce motor vehicle emissions, the CO_2 released by automobiles will almost double by 2040, as shown in Figure 1-4.

Realizing California's Climate Goals

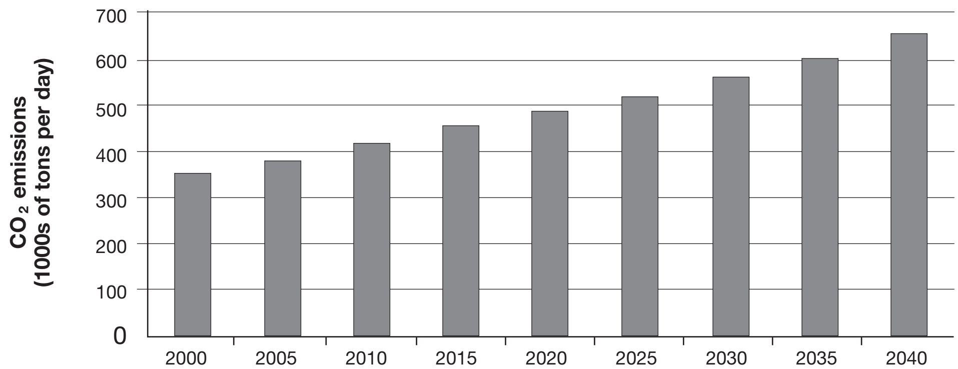
The technological potential exists for California to set standards that will serve as a model for other governments. Technologies that exist in the fleet today and more that are coming down the line will greatly reduce the impact of California's passenger vehicle fleet on the global climate.

Figure 1-3: **Contribution to CO_2 Emissions in California and Nationally (1999)**



NOTE: Includes emissions generated by imported electricity.
SOURCE: CEC, 2002 and EPA, 2003.

Figure 1-4: **Passenger Vehicle CO_2 Emissions Growth in the Absence of Regulation**



SOURCE: EMFAC 2002 (CARB, no date).

Our analysis demonstrates that a 20 percent reduction in fleet average emissions from California passenger vehicles is achievable if automakers immediately implement existing improvements in emission controls, engines, transmissions, and vehicle load reduction. Even larger reductions are possible in the next decade as new technologies that are becoming commercially viable penetrate into the fleet. These reductions are attainable without any changes to the utility and comfort that California consumers have come to enjoy in their vehicles. As California achieves its environmental goals, the state's drivers will be the beneficiaries of a clean, climate-friendly vehicle fleet.

Chapter 2

The Components of a Clean, Green Vehicle Fleet

Building cleaner, more climate-friendly cars for California does not require radical changes in the vehicles we drive today. Ample technology exists to reduce automobiles' environmental impact while maintaining the utility, comfort, and convenience California drivers have come to expect.

As shown in Table 2-1, the average vehicle in California emits almost 400 grams of heat-trapping gases from the tailpipe with each mile it drives. More than 100 additional grams of heat-trapping gases are emitted "upstream" from the vehicle, in the extraction, refining, and delivery of its fuel. Tailpipe emissions of heat-trapping gases can be reduced by a variety of vehicle improvements, many of which will result in upstream emission reductions as well.

Table 2-1: **Emissions from an Average Gasoline-Powered California Vehicle**

	Tailpipe Emissions (g CO_2-eq/mi)	Share of Tailpipe Emissions	Upstream Emissions (g CO_2-eq/mi)
HFC-134a	6.6	1.6%	n/a
N_2O	6.8	1.7%	3.0
CH_4	0.8	0.2%	12.4
CO_2	396.5	96.5%	99.0
Total	**410.7**	**100.0%**	**114.4**

NOTE: CO_2 estimate based on EMFAC 2002 output (CARB, no date). See Appendix B for estimate methodology for N_2O, CH_4, and HFC-134a. All upstream emissions estimates based on EMFAC 2002 output (CARB, no date) and GREET 1.6 emission factors (Wang, 2001).

Improvements in vehicle air conditioning systems, for example, will reduce direct and indirect emissions of heat-trapping gases. Improved catalysts can reduce CH_4 and N_2O emissions.

Vehicle modifications intended to reduce CO_2 emissions fall into three categories: vehicle load reduction, engine modifications, and transmission modifications. Improvements in vehicle accessories and reductions in inertial losses can reduce the load and drag on a vehicle. Modifications to engine design reduce friction and pumping losses and improve combustion efficiency. Transmission modifications allow the engine to operate near its optimal speed a greater percentage of the time and can also reduce mechanical losses associated with transmission operation. In addition to these modifications, renewable and biomass-based alternative fuels offer a long-term opportunity for further heat-trapping emission reductions both from the tailpipe and upstream.

Improved Mobile Air Conditioning Systems

Mobile air conditioners contribute to heat-trapping emissions by way of refrigerant leaks ("direct" emissions) and the increased accessory load associated with operating the air conditioner ("indirect" emissions). Direct emissions of refrigerants such as HFC-134a—which is 1,300 times more potent as a heat-trapping gas than CO_2—occur in all stages of the lifecycle: refrigerant manufacture, vehicle servicing and repair, and the end of the vehicle's life. The problem is compounded by accidents and system failures that result in irregular leakage of refrigerants. The average refrigerant leak rate in the European Union is approximately seven percent of the initial charge mass per year, a rate that varies according to the size of the refrigerant charge, manufacturer, vehicle age, and model (Schwarz and Harnisch, 2003).

Simulation modeling and test data show that tailpipe CO_2 emissions increase by 35 percent during air conditioning use across the SCO3 test cycle (Johnson, 2002).[2] The cumulative impact of these additional emissions is dependent on the amount of driving done with the air conditioner running. Thermal comfort modeling indicates that 13 percent of California driving (as a portion of distance traveled) is completed with the air conditioner running (Johnson, 2002).

Two pathways exist for HFC-134a emission reductions: better containment of the refrigerant through an "enhanced" 134a system or replacement of HFC-134a with an alternative refrigerant. An enhanced 134a system can substantially reduce direct emissions of HFC-134a through the use of improved hoses and better connections (Fernqvist, 2003). Improvements in compressor efficiency, condenser effectiveness, and other system changes can reduce indirect emissions (Bhatti, 1999). Results presented at the European Union's Mobile Air Conditioning Summit estimated that direct emissions of HFC-134a could be reduced up to 50 percent in an enhanced system and indirect emissions could be reduced up to 25 percent (Pettersen, 2003). The cost of such a system appears to be similar to or lower than refrigerant replacement (Pettersen, 2003).

Alternative refrigerants under consideration are CO_2 and HFC-152a. CO_2 has the advantage of having a lower GWP than HFCs and can be collected as a waste product from industrial processes. Toyota has even developed a CO_2-based air conditioning system in its hybrid fuel cell vehicle, the FCHV. However, this system is still in the early stages of development and engineers are working to improve its reliability and efficiency.

HFC-152a appears to be a very promising refrigerant replacement in the near term. The transition from one HFC to another would be fairly easy since similar components could be used, and HFC-152a has a much lower GWP (120) than HFC-134a (1,300). Furthermore, direct CO_2-equivalent emissions of refrigerant from a 152a system can be reduced by 95 percent or more relative to a baseline 134a system as a result of the smaller refrigerant charge, lower leak rate, and lower GWP. Indirect CO_2 emissions can be reduced by up to 10 percent (Hill, 2003). Although there are some safety concerns associated with leaks from 152a systems, these appear to be manageable with system design modifications (European Commission, 2003).

Improved Catalysts

The most promising method to reduce CH_4 and N_2O emissions from motor vehicles is improved catalyst technology. CH_4 emissions result from incomplete combustion of gasoline and tend to be higher during cold starts. Because CH_4 is more difficult to oxidize than other hydrocarbons, current vehicle catalyst systems do not control these emissions as well as they do other hydrocarbons. And, as with other pollutants, CH_4 emissions increase as a catalyst ages. Nonetheless, measured CH_4 emissions have decreased on vehicles with tighter tailpipe standards (Lipman and Delucchi, 2002), and further reductions are likely as cold-start emission controls improve. Such reductions will be needed to meet California's LEV II tailpipe emission standards.

The formation and control of N_2O emissions are less well understood than CH_4 emissions. Several chemical mechanisms have been proposed for N_2O formation depending on the

[2] The SCO3 is a 594-second test cycle designed to measure emissions from vehicles right after startup and during air conditioning use, under the conditions set forth in 40CFR86.161-00 and the driving schedule described in 40CFR86 Appendix I, part h.

type of emission control system in use (Lipman and Delucchi, 2002; Odaka et al., 2000; Koike et al., 1999). In addition, N_2O emissions have been associated with high levels of sulfur in gasoline (Baronick et al., 2000). N_2O formation and emissions are highest at low catalyst temperatures, which suggests that improvements in catalyst technologies that reduce cold-start emissions should also decrease N_2O emissions.

Vehicle Load Reduction

Loads are placed on a vehicle by forces that resist motion (drag and rolling resistance) and systems that draw energy from the vehicle (such as the air conditioner, power steering, and lighting). Drag and rolling resistance are represented by the coefficient of drag, C_d, and the coefficient of rolling resistance, C_r, respectively. Vehicle design modifications that help a vehicle move along the road through reductions in C_d or C_r will result in lower CO_2 emissions. Similarly, reductions in a vehicle's accessory load can improve its efficiency.

The ease with which a vehicle moves through the air (i.e., its ability to overcome drag) is determined by its shape and profile. Vehicle drag is proportional to the size of a vehicle's frontal area and its C_d. Automakers generally attempt to improve aerodynamics by reducing a vehicle's C_d rather than its frontal area, which often requires downsizing the vehicle. Currently, a typical car has a C_d of approximately 0.3 to 0.35 and a typical light truck has a C_d of 0.4 to 0.45 (An et al., 2002). Vehicle redesigns have often reduced the C_d as much as 15 percent, and such reductions are possible throughout the next decade (An et al., 2002). For example, the new Toyota Prius has a C_d of 0.26 and the GM EV1 achieved a C_d of 0.19.

In addition to the drag produced as a vehicle moves through the air, resistance is created by the contact between the vehicle's tires and the road. Tires with low rolling resistance, which are available on many new vehicles and to some degree on the secondary market, reduce this friction and, therefore, the load on the vehicle. Further reductions in rolling resistance are possible through modifications in tire composition, such as increased use of silica (Friedrich, 2003). Low rolling resistance tires do not necessarily compromise vehicle safety or tire longevity (CEC, 2003a), and an added benefit is that they could reduce heat-trapping emissions from the in-use vehicle fleet as well as from new vehicles if they are able to penetrate the replacement tire market.

Additional load reduction can be achieved through alterations in a vehicle's electrical system. Current systems operate at 12V, but many manufacturers are considering a transition to 42V systems to support the increasingly demanding electrical accessories on today's vehicles. Higher voltage will not only improve accessory efficiency and allow for the use of more electrically powered accessories, such as water pumps and power steering, but will also reduce the heat-trapping emissions associated with accessory use.

The 5 to 15 percent of vehicle CO_2 emissions that occur when a vehicle is stopped and idling (An et al., 2002) can be addressed with a starter-generator. This technology reduces heat-trapping emissions by turning the engine off when the engine is idling (e.g., at a traffic light, sitting in traffic, or during deceleration). Accessories such as the radio and an electric air conditioning system continue to function; when it is time to go, the engine restarts. Advanced starter-generators also enhance drivability through improvements in low-end torque and reduced engine vibration (DeCicco et al., 2001). The addition of a starter-generator does not turn a conventional vehicle into a hybrid-electric vehicle (HEV), but it does deliver one of the benefits of an HEV.

There are two types of starter-generator technology for replacing starter motors and alternators in existing vehicle architecture: integrated starter-generators (ISGs) and belt-driven starter-generators (BSGs). ISGs require a 42V electrical system, but, as mentioned above, this enables the electrification of vehicle features such as power steering (Cho et al., 2000). As the name implies, an ISG is integrated into the vehicle system, often between the engine and transmission, requiring a more radical design change and entailing higher costs. A BSG, on the other hand, can replace existing alternators and operate within the current 12V electrical system. Therefore, BSGs require fewer design changes and result in lower costs (Henry et al., 2001). The costs are further reduced relative to ISGs because BSGs typically operate with a lower-power motor.

Improved Engines

Internal-combustion engines lie at the heart of modern mobility. Engine modifications for reducing heat-trapping emissions aim to accomplish one or more of three goals: reducing engine friction, reducing pumping losses, and improving fuel combustion. Several modifications that achieve these goals are possible and in use today in the United States and around the world.

Low-friction lubricants and low-friction engine components, for example, can reduce energy loss in the engine caused by friction between engine parts (valve train, pistons, and bearings). Studies have shown that the use of low-viscosity oils in the engine can reduce this frictional loss without affecting engine durability (Taylor and Roy, 2000).

Pumping losses occur when air being pulled into a cylinder or exhaust gas being pushed out passes by an obstruction. Many of the obstructions in today's engines can be reduced or eliminated, and engine operation can be modified to minimize pumping losses. One way is to equip each cylinder with four valves, thus creating a larger effective area through which air can enter the cylinder and exhaust gas can leave. The design of these valves and how they are operated can also increase combustion efficiency by enhancing the mixture of air and fuel before they are burned. Close to 60 percent of cars and 25 percent of SUVs sold nationally in 2000 were equipped with four valves per cylinder, so there is significant room for further penetration into the fleet (Hellman and Heavenrich, 2003).

Further control of airflow is possible through variable valve control. These systems vary the timing and/or lift of the engine valves as a function of engine operating conditions. Engines equipped with variable valve timing (VVT) reduce pumping losses and improve air-fuel mixing—leading to more efficient combustion—by adjusting the timing of the opening and closing of valves relative to engine speed. Variable valve lift and timing (VVLT) combines VVT with variable valve lift. These technologies optimize the intake and exhaust processes across a wide range of engine operating conditions and are becoming more common on vehicles sold today. Some form of variable valve control (VVT, VVLT, or Honda's VTEC) is available on close to one-quarter of MY 2003 vehicle engines, but these engines are not evenly distributed among manufacturers. While Honda and Toyota feature variable valve control on 89 and 70 percent of their engines used in North America, respectively, other manufacturers—particularly American manufacturers—have a much lower percentage (Ward's Communications, 2003b).

Another way to reduce heat-trapping emissions from vehicle engine operation is to use only a portion of the engine whenever full power is not needed. Closing the intake and exhaust valves on some of an engine's cylinders at low or modest power levels, as in highway cruising, reduces the engine's energy consumption. All the cylinders are used for rapid acceleration and hauling heavy loads, and the transition between full and partial cylinder usage is seamless. The benefits of this technology obviously depend on vehicle use and driving patterns; currently, it is being used primarily for large engines. General Motors (GM), for example, recently announced that cylinder deactivation, or displacement on demand (DOD), will be available on several of its large trucks starting in MY 2005. GM estimates that by 2008, two million GM vehicles will be sold with DOD (GM, 2003). Honda will also employ cylinder deactivation on the six-cylinder Accord hybrid, and Mercedes-Benz uses it on many of its sedans with large engines.

Several additional engine technologies are emerging in the vehicle market, including an advance in variable valve control: removal of the engine throttle. Unless a typical engine is operating at full power, its throttle valve will be partially closed, thereby restricting the flow of air to the engine and creating a pumping loss. Recently, BMW introduced the Valvetronic throttleless engine on some of its 3 Series sedans (Jost, 2002). This design strategy, which relies on electronically controlled variable valves rather than the throttle valve to control air flow into the engine cylinders, is an advanced form of VVLT known as intake valve throttling. BMW estimates that use of the Valvetronic engine on one of its compact models will result in a nearly 10 percent reduction of CO_2 emissions (BMW, 2002).

Frictional losses in an engine are roughly proportional to engine size, so smaller engines will reduce frictional losses and, therefore, CO_2 emissions. Changes such as four valves per cylinder, VVT, VVLT, and throttleless operation can provide this friction reduction benefit by increasing the power density of an engine (i.e., enabling a smaller engine to achieve the same power as a larger engine).

Additional engine size reductions can be made without sacrificing performance by incorporating a turbocharger or supercharger (as Volkswagen and Saab do on many of the vehicles they sell in the United States). A turbocharger enhances engine power by delivering compressed air into the cylinders, allowing more fuel to enter the cylinder as well. Adding electrical assist to a turbocharger can reduce the "lag" the driver feels when the turbocharger is activated.

Another emerging technology is the direct-injection engine, which, by providing more control over the flow of fuel into the cylinder, helps improve fuel mixing and engine efficiency and reduce throttling losses. "Lean-burning" direct-injection engines—those that run with excess air—achieve the greatest gains in efficiency, but excess air fosters the formation of high levels of nitrogen oxides (NOx). Since current emission control equipment cannot bring NOx levels in line with new tailpipe emission standards (Eichlseder et al., 2000), direct-injection engines may need to run at stoichiometric conditions (i.e., without excess air) unless improvements in exhaust treatment technologies are realized.

Other engine technologies in the research and development phase show promise for future emission reductions. Camless valve actuation, for example, extends the idea of VVT by removing the camshaft altogether. Valves can be opened and closed using a number of different systems such as electromechanical solenoid-controlled spring-mass valve systems (NAS, 2002). Like variable valve control, camless valve actuation reduces pumping losses associated with valves as well as frictional losses at the camshaft.

Variable compression ratio (VCR) engines offer the potential to vary the engine compression ratio (the volume of the cylinder divided by the volume that remains when the piston is at top dead center) according to driving demands. Current engines operate at a fixed compression ratio because at high compression ratios, gasoline can ignite prematurely, leading to engine knocking. To prevent this from occurring, the compression ratio must be kept low under high-load operating conditions (i.e., a wide-open throttle). On the other hand, combustion efficiency increases with compression ratio, so a high compression ratio would be favorable under low-load operating conditions when cylinder conditions are less likely to produce engine knocking. VCR engines attempt to resolve this dilemma, but none are in production and a number of design and structural hurdles must be overcome before this technology can be used in commercially available vehicles (Schwaderlapp et al., 2002; Roberts, 2003).

Homogeneous-charge compression-ignition (HCCI) engines, which rely on compression rather than a spark to ignite a pre-mixed air-fuel mixture, draw their efficiency gains from three sources: no throttling losses, use of higher compression ratios, and shorter combustion duration (Epping et al., 2002). These engines have substantially lower NOx and particulate matter (PM) levels than compression-ignition diesel engines and can operate on a wide variety of fuels, including gasoline, propane, and natural gas. Two problems with the technology are its high rate of carbon monoxide (CO) and hydrocarbon (HC) emissions and its inability to maintain combustion stability over varying loads (Epping et al., 2002; Aceves et al., 2001).

Advanced Diesel Engines

Diesel engines offer some advantages over gasoline engines that could lead to lower heat-trapping emissions, but these reductions come at a price. Emissions of NOx, a precursor to ozone (the primary constituent of smog), and diesel PM, classified as a toxic air contaminant by CARB (2000), are higher from diesel engines than gasoline engines. Diesel PM formation is caused by poor air-fuel mixing that leads to pockets of fuel-rich areas. The high temperatures associated with a diesel engine's high compression ratios lead to the formation of thermal NOx, and diesel's typically oxygen-rich exhaust limits the ability of current catalyst technology to reduce NOx emissions. Effective PM and NOx controls are a major focus of current diesel development activities, and promising progress has been demonstrated in recent prototypes.

The benefit of lower heat-trapping emissions offered by diesel engines (relative to comparable gasoline engines) is the result of higher compression ratios and attendant improvements in combustion efficiency. Newer throttleless, direct-injection diesel engines also experience lower pumping losses than conventional gasoline engines. Nevertheless, the emission control systems required to protect public health and the higher engine cost make diesel vehicles more expensive than comparable gasoline vehicles. Diesel, therefore, may not be as cost-effective a global warming reduction strategy as improved gasoline vehicles (Monahan and Friedman, 2004).

Diesel vehicles are unable to meet current U.S. tailpipe emission standards, and they face an even bigger hurdle in California, where stricter LEV II emission standards take effect in MY 2004. Advances in emission control technology would likely enable diesel to meet California's emission standards over the coming decade, but other important issues still need to be resolved. More research into the toxicity of PM emissions should be conducted, and more attention needs to be paid to in-use compliance by diesel vehicles (which are currently exempt from California's

Smog Check program). A better understanding of the impact black carbon has on the climate could necessitate further controls on diesel engines.

Transmission Modifications

A vehicle's transmission takes the power generated by the engine and sends it to the wheels so the vehicle can move. Because an engine has a narrow range of speed for optimal performance (i.e., power and torque), it cannot be coupled directly to the wheels, which would force the engine to operate at a wide range of speeds and torque levels. Instead, by allowing the transmission to change gear ratios, the engine can operate near its optimal speed a greater percentage of the time.

Heat-trapping emissions can be reduced by modifying a vehicle's transmission in one of two ways. The first is by allowing the engine to operate closer to its optimal speed a greater proportion of the time. The second is by reducing mechanical and frictional losses associated with transmission operation (i.e., directly improving transmission efficiency).

Most vehicles sold in the United States have an automatic transmission—close to 88 percent of MY 2000 cars and more than 90 percent of MY 2000 light trucks (Hellman and Heavenrich, 2003). By adding more speeds to an automatic transmission, the engine can operate at its optimal speed a greater percentage of the time, improving engine efficiency and reducing heat-trapping emissions. Torque limitations on the current generation of continuously variable transmissions (discussed below) mean that five-and six-speed automatic transmissions are the transmission modification best suited to reduce heat-trapping emissions from most larger light-duty trucks in the near term. These transmissions have already begun to penetrate the current vehicle market, especially for cars.

The natural extension of adding more speeds to a transmission is adding an infinite number of gears. Essentially, this is what a continuously variable transmission (CVT) does. Rather than using a fixed set of discrete gear ratios as in a conventional transmission, a CVT uses a belt-and-pulley configuration that allows for continuous variation in the effective gear ratio. CVTs are currently limited to passenger cars and lighter light-duty trucks because of torque limitations, but development of a chain CVT could extend the application of this technology to heavier light trucks. A limited number of vehicles now offer CVTs as standard equipment, including six MY 2003 cars (of 498 available) and five MY 2003 SUVs, pickups, and vans; they are optional on an additional three cars (Ward's Communications, 2003b).

Aggressive shift logic is another way to more closely match engine speed with driving conditions. Despite the fact that this enhancement would provide optimized shift schedules and improved logic, there is some concern about consumer acceptance because drivers will notice more frequent shifting as the transmission adjusts more often to driving demands. Well-implemented control strategies and good design, however, can overcome these issues. Aggressive shift logic can be integrated with any of the transmission technologies discussed above.

Finally, removing the torque converter is another way to improve an automatic transmission's operating efficiency. A torque converter is a fluid coupling that allows the engine to spin somewhat independently of the transmission and wheels, similar to the clutch in a manual transmission, and uses a pump and transmission fluid to transfer engine rotation to the wheels. Replacing the torque converter with an electronically controlled clutch mechanism eliminates losses. Similarly, a dual-clutch transmission eliminates the need for a torque converter by allowing the engine to remain engaged during gear shifting.

Hybrid-Electric Vehicles (HEVs)

Three models of HEVs are on U.S. roads now and several more will be introduced over the coming months and years. HEVs combine an internal-combustion engine with advanced electrical components that shut off the engine while idling, enable regenerative braking, allow for the use of a downsized engine while maintaining performance, and, in some cases, provide electric-only driving. Today's HEVs offer significant environmental benefits, and future models, like conventional vehicles, will benefit from the incorporation of advanced engine and transmission technologies that are not yet available.

What exactly constitutes an HEV is difficult to define because there are different degrees of hybridization, but all HEVs share at least three characteristics: a downsized internal-combustion engine; an electric motor that helps the engine drive the wheels and shuts the engine off while idling; and regenerative braking, which enables the electric motor to assist in braking and store the recovered energy in a battery. Some HEVs, known as "full" hybrids, are also capable of electric-only driving, while "plug-in" hybrids offer extended battery-electric range (Friedman, 2003). In the end, however, the key metric for comparing HEVs is their emissions performance.

Technologies in Use

Technologies for reducing heat-trapping emissions from motor vehicles do not exist only in automotive laboratories or peoples' imaginations. Many of the technologies discussed above are already being used in vehicles available on the market today. Table 2-2 illustrates some of the technologies currently in use.

Table 2-2: **Current Vehicles with Technologies for Reducing Heat-Trapping Emissions**

	Vehicle Models
Engine Technologies	
VTEC	Most Honda vehicles
Variable valve timing	Most Toyota vehicles, Ford F-150 (5.4 L Triton)
Cylinder deactivation	Honda Accord (V6), GM Vortec V8 engine family
Throttleless engine	BMW 3 series
Transmission Technologies	
Continuously variable transmission	Nissan Murano, Mini Cooper, Saturn Ion, Saturn Vue, Toyota Prius, Honda Civic Hybrid, Honda Civic CNG
6-speed automatic transmission	Jaguar S-Type and XK series
Dual-clutch transmission	Audi TT 3.2 Quattro
Hybrid-Electric Vehicles	
	Honda Civic, Honda Insight, Toyota Prius, Ford Escape (announced), Toyota Camry (announced)

Alternative Fuels

Modifications to conventional vehicles offer the swiftest way to secure heat-trapping emission reductions in the near term, but they are not the only solution. Alternative-fuel vehicles (AFVs), for example, operate on non-petroleum-based fuels and can provide substantial reductions in heat-trapping emissions. Indeed, meeting aggressive climate goals will likely require the introduction of alternative fuels and AFV technologies in the coming years.

AFVs cannot be compared with conventional vehicles solely on the basis of tailpipe emissions. The upstream emissions associated with fuel extraction, refining, and transport can have a significant impact on a vehicle's lifetime impact. For instance, biofuels have an important additional upstream emission benefit associated with carbon sequestration (the natural uptake of carbon into the feedstock materials, or plants, grown for this purpose), but other alternative fuels have energy-intensive extraction and production processes that lessen or eliminate their emission benefits at the tailpipe. Evaluation of alternative fuels requires a full fuel cycle or "well-to-wheels" (WTW) analysis in order to put their environmental benefits and costs in the proper context (MacLean and Lave, 2003; 2000; Lave et al., 2000; IEA, 1999).

Another important consideration in evaluating alternative fuels is determining how often they will actually be used in a given vehicle. Many vehicles sold today are called flex-fuel vehicles because they can operate on either gasoline or fuel that is 85 percent ethanol by volume (E85), but due to the lack of availability and cost of E85, these vehicles almost always operate on gasoline and realize none of the potential climate benefits of E85. Therefore, it is crucial that alternative fuels be used in vehicles that will either run on that fuel exclusively or provide a verification mechanism to accurately account for potential heat-trapping emission benefits.

Ethanol

Ethanol, an alcohol, has a lower energy content than gasoline but, when blended with gasoline, enables spark-ignited engines to operate at higher compression ratios, thereby increasing overall engine efficiency and reducing fuel usage. Low amounts of ethanol are currently blended into California gasoline to meet the oxygen weight requirements outlined in the Clean Air Act Amendments of 1990 (5.7 percent ethanol by volume).[3] Blends featuring higher amounts are also available.

The means by which ethanol is produced have an important effect on its heat-trapping emission reduction benefits. For example, most ethanol in the U.S., which is produced in the Midwest from corn, provides a small heat-trapping emission reduction benefit (Wang et al., 1999). Lignocellulosic ethanol, on the other hand, offers a renewable transportation fuel with very low net heat-trapping emissions. The source of this ethanol, lignocellulosic biomass, is woody or herbaceous plant matter grown on dedicated energy plantations or derived from farm waste.

While lignocellulosic ethanol is produced by converting the sugars in the biomass (cellulose), the non-fermentable portion (lignin) is combusted to produce steam, which can then be used for heating or to generate electricity that can power the production facility or be distributed through the grid. Furthermore, the carbon sequestered during lignocellulosic biomass production provides an additional emission reduction benefit.

This combination of benefits results, in some scenarios, in a net reduction of heat-trapping

[3] Current California reformulated gasoline (CARFG) regulations cap ethanol content at 10 percent by volume (3.5 percent oxygen by weight).

gases. Though the production of lignocellulosic ethanol is not economically viable on a large scale at this time, conditions could change during the next decade (Wooley et al., 1999).

Compressed Natural Gas (CNG)

CNG, which is used in some spark-ignited vehicle engines today, has a higher octane rating than gasoline (allowing the vehicle engine to operate at higher compression ratios), better air-fuel mixing, and, therefore, higher combustion efficiency. Overall, CNG is cleaner-burning and has a lower flame temperature, resulting in lower rates of tailpipe pollutant emissions. CNG vehicles also have lower cold-start HC and in-use NOx emissions than gasoline vehicles (Raine et al., 1997).

Many of these emission reduction benefits are attributable to the cleaner methods of extracting and producing CNG compared with gasoline, but the benefits are dependent on the source of the natural gas used as a feedstock. Given the high demand for natural gas in electricity generation, it is possible that it will need to be imported from outside North America if transportation demands increase. This will increase heat-trapping emissions associated with the fuel because it is generally liquefied before transport, increasing energy use and yielding some methane boil-off during transport, not to mention the emissions associated with tankers and barges. WTW analyses of vehicles using non-North American CNG do not show a significant benefit in reducing heat-trapping emissions (GM et al., 2001a; 2001b).

Hydrogen

Several state and federal programs are promoting the use of hydrogen as a future transportation fuel for fuel cell vehicles and internal-combustion engines. Currently, the U.S. space program uses hydrogen combustion, and some demonstration automobiles have been produced with a hydrogen internal-combustion engine (U.S. DOE, 2002a).

Hydrogen fuel cells represent the long-term ideal for clean transportation. This highly efficient technology uses an electrochemical reaction to produce electricity, allowing a fuel cell vehicle to travel several times farther per unit of energy than a traditional gasoline vehicle.

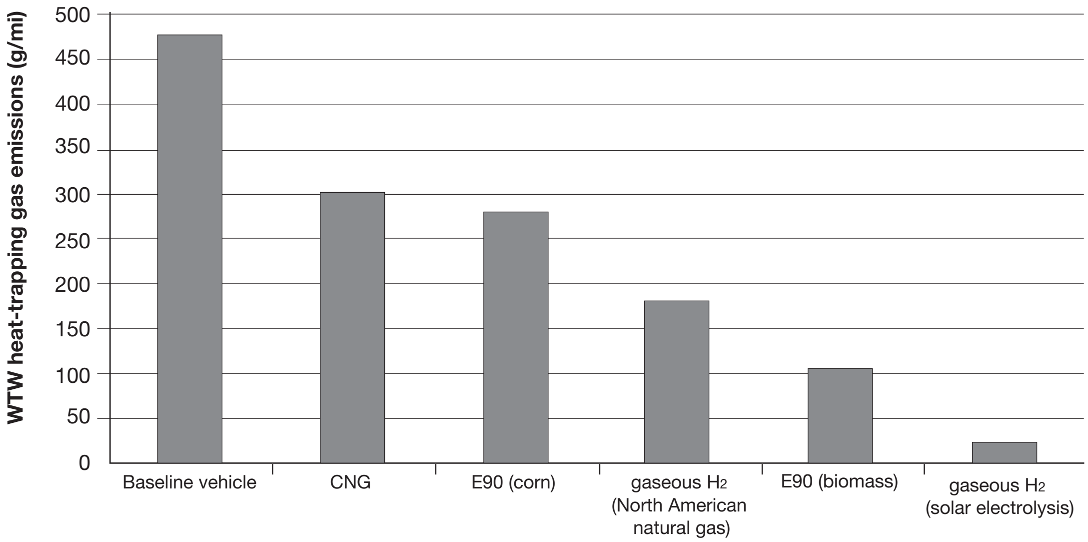
But, as with ethanol, we must focus on production pathways to realize the full benefits of hydrogen. At the present time, 95 percent of the hydrogen used in the United States is produced by steam methane reforming with natural gas or other light HCs as the feedstock (U.S. DOE, 2002b). Another production method is electrolysis, which uses electricity to split water molecules into hydrogen and oxygen. The total emissions from electrolysis depend on the source of the electricity used, but the process can actually be emissions-free if renewable energy sources are used.

Other methods of hydrogen production including solar processes, thermochemical water splitting, and biological techniques remain in developmental phases (U.S. DOE, 2002b). For all methods of hydrogen production other than electrolysis powered by the current U.S. electricity generation mix, hydrogen fuel cell vehicles could deliver a 30 to 90 percent reduction in WTW heat-trapping emissions relative to conventional gasoline vehicles (Wang, 2002).

Comparing the Potential of Alternative Fuels

Figure 2-1 (p. 20) compares WTW heat-trapping emissions from several AFVs (measured in grams per mile). These results are based on output from Argonne National Laboratory's Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model using long-term, California-based assumptions (Wang, 2001).

Figure 2-1: **Well-to-Wheels Heat-Trapping Gas Emissions from Alternative-Fuel Vehicles**



SOURCE: GREET 1.6.

As the figure illustrates, AFVs show tremendous promise for reducing heat-trapping emissions from the California vehicle fleet over the long term. Readily available fuels such as CNG offer some opportunities for emission reductions today (using natural gas from North America), but the development and commercialization of biomass-based ethanol and renewably produced hydrogen are crucial steps to significantly reducing the California vehicle fleet's impact on the global climate. Therefore, research, development, and demonstration projects must move forward in these areas while we attempt to obtain the largest emission reductions possible with advances in conventional vehicle and HEV technology.

Chapter 3

The Path to a Clean, Green Fleet in California

More than 1.5 million passenger vehicles are sold in California each year (EIA, 2004), and thanks to California's low-emission vehicle (LEV) and zero-emission vehicle (ZEV) programs, these automobiles have a much smaller impact on local air quality than they did 20 years ago. Sadly, though, emissions of heat-trapping gases have continued to increase, pumping more than 10 million tons of CO_2 into the atmosphere every year. An MY 2000 passenger vehicle sold in California will emit close to 90 tons of heat-trapping gases from its tailpipe during its lifetime, and an additional 10 tons will be released as a result of fuel extraction, refining, and distribution.[4]

Building Cooler Cars for California

The technology exists today to reduce the global warming impact of California's motor vehicle fleet. In fact, we can build vehicles that meet all of our transportation, passenger-ferrying, and load-hauling needs but have a much smaller environmental footprint. The technologies discussed in the previous chapter can be combined and applied to vehicles in a variety of packages.

For the purposes of this report, the Union of Concerned Scientists assembled different levels of technology into two packages and simulated the effect they would have on vehicle performance and emissions. Our first package combines technologies currently in use and available somewhere in the U.S. vehicle fleet as of MY 2004. Producing actual vehicles like those modeled here would not require the development of new technology—just the increased penetration of technology currently on the road.

Our second technology package focuses on vehicle load reduction and engine, transmission, and air conditioning improvements that will become available in the next decade. In most cases, automakers and suppliers have announced plans to introduce these technologies over the next five years.

Table 3-1 lists the technologies modeled in our simulations. It is important to note that

Table 3-1: **Technologies Included in Simulations**[a]

Engine Technologies	Vehicle Load Reduction
Variable valve control	Aerodynamic drag reduction[b]
Engine friction reduction	Engine accessory improvement
4 valves per cylinder	Tire rolling resistance reduction[b]
Cylinder deactivation	Idle speed reduction
Stoichiometric direct-injection engine	
Transmission Technologies	**Other**
6-speed automatic transmission	Low-leak 134a air conditioner
Continuously variable transmission[c]	*42V integrated starter-generator*
Dual-clutch transmission, 6-speed without torque convertor	*HFC-152a air conditioner*

NOTES: a. Italics denote technologies only included in advanced case.
b. Aerodynamic drag and rolling resistance are reduced more aggressively in the advanced technology package.
c. Used in the small car in both the moderate and advanced cases.

[4] Calculation based on upstream emission factors from GREET 1.6 (Wang, 2001) using CARFG with ethanol as an oxygenate.

these technology packages do not represent the only way to achieve emission reductions. They are simply two examples of many that can show how conventional technologies should be used to reduce heat-trapping emissions.

Each of the technologies modeled provides an emission reduction benefit. However, simulation modeling is necessary in order to capture the synergistic and overlapping effects of these technologies when they are applied to a vehicle alongside one another. Vehicle emission levels and performance were simulated for the baseline vehicles and both of the case study packages using the Modal Energy and Emissions Model (MEEM), a comprehensive vehicle power-demand model. MEEM predicts modal tailpipe emissions during the course of a defined test cycle by using a set of vehicle operating parameters to simulate vehicle power demand and operating conditions (NCHRP, 2001).

In order to represent the California vehicle fleet, we simulated top-selling vehicles in five vehicle classes: a Ford Focus (small car), a six-cylinder Toyota Camry (large car), a Dodge Grand Caravan (minivan), a six-cylinder Ford Explorer (sport utility vehicle, or SUV), and an eight-cylinder Chevrolet Silverado (pickup truck). These vehicles were selected because they are close to the average heat-trapping emission level, engine size and power, and performance in their respective vehicle classes. Information on each vehicle's power-train, emissions, and performance characteristics was collected from a variety of sources including *Consumer Reports* and Edmunds.com (see Appendix C for detailed vehicle information).

It should be noted that the selected vehicles, as a whole, are slightly lower-emitting and better-performing than the average vehicle sold in the United States, suggesting that the emission reductions modeled could slightly underestimate the

Table 3-2: **Baseline Heat-Trapping Emissions and Performance of Modeled Vehicles**

	Small Car	Large Car	Minivan	SUV	Pickup	Fleet Average
	Ford Focus	Toyota Camry	Dodge Grand Caravan	Ford Explorer	Chevrolet Silverado 1500	
Market share	32%	25%	15%	18%	10%	
Emissions (g CO_2-eq/mi)						
CO_2-cert	266.4	306.0	338.9	407.2	452.2	331.8
CO_2-a/c	12.1	13.9	15.4	18.5	20.6	15.1
HFC-134a	6.7	6.7	6.7	6.7	6.7	6.7
CH_4	0.8	0.8	0.8	0.8	0.8	0.8
N_2O	6.8	6.8	6.8	6.8	6.8	6.8
Total	**292.9**	**334.2**	**368.6**	**440.0**	**487.1**	**361.3**
0 to 60 time (sec)	9.9	8.7	9.7	9.3	9.6	

NOTE: CO_2-cert is based on vehicle certification data. CO_2-a/c (CO_2 from air conditioner operation) is estimated based on Johnson, 2002. HFC-134a, CH_4, and N_2O are UCS estimates. 0 to 60 times are from *Consumer Reports*. Market share data provided by Mike Jackson.

Table 3-3: **Estimated Emission Reductions from Air Conditioner Modifications**

System Improvement	Direct Emission Reduction (% CO_2-eq)	Indirect Emission Reduction (% CO_2-eq)	Cost
Enhanced 134a	50%	25%	$50
Refrigerant replacement with HFC-152a	95%	10%	$50

NOTE: $50 was assumed to be a conservative retail price increase based on the sources listed below.

SOURCE: Pettersen, 2003 and Hill, 2003.

emission reduction potential in the California vehicle fleet. Table 3-2 shows the emissions from each of the five selected vehicles along with fleet average emissions based on California market share data. Estimates for CH_4, N_2O, and HFC-134a emissions were estimated based on relationships obtained from a literature review (see Appendix B for details on data and methodology).

After calibrating MEEM to match the performance and emissions of our MY 2003 baseline vehicles, we simulated the CO_2 emissions from vehicles modified with our two technology packages over the course of the federal city and highway test cycles. The vehicles modeled match MY 2003 weight and size. The only changes we made to the baseline vehicles for the purposes of our case studies are in the drivetrain and vehicle loads, excluding weight reduction. The conventional emission control system changes needed to meet California's stringent LEV II standards are part of our baseline.

Because the federal city and highway test cycles do not include air conditioning operation, we estimated potential emission reductions from air conditioning modifications outside the MEEM environment. These estimates were assumed to be uniform across the vehicle fleet and are shown in Table 3-3.

Estimating the Cost of Technology Packages

To assess the cost-effectiveness of the modeled technological improvements, we surveyed the literature to determine the cost of each technology as applied to our vehicles. Cost estimates for vehicle load reduction, engine modifications, and transmission improvements were collected through interviews with vehicle component manufacturers and suppliers conducted by Plotkin et al. (2002). Cost estimates for air conditioner modifications were collected from presentations given in 2003 at the European Union's Mobile Air Conditioning (MAC) Summit in Brussels (Pettersen, 2003). See Appendix B for detailed cost data.

Lifetime costs associated with our technological improvements are based on a 16-year vehicle lifetime and vehicle miles traveled by vehicle age for California passenger cars and light trucks, as estimated by EMFAC 2002, California's mobile-source emission factor model (CARB, no date). We have discounted future costs by five percent—the difference between an average auto loan (seven percent) and inflation (two percent).

The Potential for Climate-Friendly Cars Today

Applying technologies available today to more new vehicles can achieve large emission reductions while maintaining vehicle performance and utility. We measure this potential by applying our moderate technology package to the five simulated vehicles.

As depicted in Table 3-4, these modifications to a Ford Explorer will result in an almost 25 percent reduction in heat-trapping emissions. In addition to their environmental benefits, these reductions will also benefit the driver. Because the additional cost of the technology improvements on the new Ford Explorer will be more than offset over the vehicle's lifetime by fuel savings associated with some of the emission-reducing technologies, the driver will ultimately save more than $2,500. In fact, the additional cost of the technology will be made up in less than two years of driving.

SUVs are not the only vehicles that can benefit from the application of new technology. Reductions are possible in all vehicle classes, including small cars, minivans, and pickup trucks. Even Toyota, manufacturer of some of today's most climate-friendly cars, can achieve reductions in emissions from its popular family sedan, the Camry. Because the Camry already has a relatively low drag coefficient, C_d was only reduced by five percent in our modeling rather than 10 percent for the other simulated vehicles. Similarly, because the base Camry engine already offers four valves per cylinder, that feature was not included in the modeled package. Table 3-5 shows the emis-

Table 3-4: **A Cooler Ford Explorer**

Engine	Emissions Performance	
6-cylinder variable valve lift and timing, cylinder deactivation, 4 valves per cylinder, and engine friction reduction	Baseline heat-trapping gas emissions Improved heat-trapping gas emissions % reduction	440 g CO_2-eq/mi 333 g CO_2-eq/mi 24%
Transmission	**Lifetime Impact**	
6-speed automatic transmission	Heat-trapping gas emissions reduced	29 tons
Vehicle	**Performance**	
C_d reduced 10% C_r reduced 10%	0 to 60 acceleration 0 to 60 acceleration towing 1,500 lbs	9.3 sec 11.6 sec
Air Conditioning	**Cost**	
Enhanced 134a system	Retail price increase Payback time	$620 1.9 years

NOTE: Mileage estimates from EMFAC 2002 (CARB, no date). Assumptions are a 16-year vehicle lifetime, a gasoline price of $1.68/gallon, and a real discount rate of 5%. Lifetime heat-trapping emission reductions are estimated using the well-to-wheels emission factor for California reformulated gasoline from GREET 1.6 (Wang, 2001).

Table 3-5: **A Cooler Toyota Camry**

Engine	Emissions Performance	
6-cylinder variable valve lift and timing, cylinder deactivation, 4 valves per cylinder, and engine friction reduction	Baseline heat-trapping gas emissions Improved heat-trapping gas emissions % reduction	334 g CO_2-eq/mi 271 g CO_2-eq/mi 19%
Transmission	**Lifetime Impact**	
6-speed automatic transmission	Heat-trapping gas emissions reduced	16 tons
Vehicle	**Performance**	
C_d reduced 5% C_r reduced 10%	0 to 60 acceleration	8.7 sec
Air Conditioning	**Cost**	
Enhanced 134a system	Retail price increase Payback time	$620 3.9 years

NOTE: Mileage estimates from EMFAC 2002 (CARB, no date). Assumptions are a 16-year vehicle lifetime, a gasoline price of $1.68/gallon, and a real discount rate of 5%. Lifetime heat-trapping emission reductions are estimated using the well-to-wheels emission factor for California reformulated gasoline from GREET 1.6 (Wang, 2001).

sion reductions achieved when we apply our package of currently available technology to the Camry.

These simple modifications could reduce heat-trapping emissions close to 20 percent, and the additional cost would be made up in less than four years of operating the vehicle. Similar incremental technology improvements could reduce the heat-trapping emissions from small cars, pickup trucks, and minivans by 18, 21, and 18 percent, respectively. The additional costs associated with these emission reductions would be made up in less than five years of driving the small car and minivan and approximately two years of driving the pickup truck.

Full realization of this technological potential could achieve a 20 percent reduction in fleet average heat-trapping emissions released by new passenger vehicles sold in California. These vehicles would meet all the expectations of California drivers while lessening the fleet's impact on the environment. Some technological modifications would even save consumers money over a vehicle's lifetime through reductions in fuel usage.

The Next Generation of Climate-Friendly Cars

While realizing the emission reductions that can be accomplished with existing technology is a crucial step in the right direction, even larger reductions are possible with advances in technology that are expected during the next few years. Appropriate policies would encourage the development and deployment of these new technologies, which include gasoline direct-injection (GDI) engines (available in some form in Japan and Europe), transmissions that do not require a torque converter (available in select models today), and additional reductions in vehicle loads made possible by improvements in vehicle accessories, aerodynamic drag, and rolling resistance.

In addition, advancements in vehicle electronics slated to go into production in the next three years will enable start-stop technology on most

Table 3-6: A Next-Generation Ford Explorer

Engine	Emissions Performance	
6-cylinder advanced stoichiometric GDI, variable valve control, and cylinder deactivation	Baseline heat-trapping gas emissions Improved heat-trapping gas emissions % reduction	440 g CO_2-eq/mi 251 g CO_2-eq/mi 43%
Transmission	**Lifetime Impact**	
6-speed dual-clutch transmission without torque converter	Heat-trapping gas emissions reduced	57 tons
Vehicle	**Performance**	
C_d reduced 20% C_r reduced 20% Improved accessories Idle off	0 to 60 acceleration 0 to 60 acceleration towing 1,500 lbs	9.1 sec 11.4 sec
Air Conditioning	**Cost**	
HFC-152a system	Retail price increase Payback time	$1,960 3.2 years

NOTE: Mileage estimates from EMFAC 2002 (CARB, no date). Assumptions are a 16-year vehicle lifetime, a gasoline price of $1.68/gallon, and a real discount rate of 5%. Lifetime heat-trapping emission reductions are estimated using the well-to-wheels emission factor for California reformulated gasoline from GREET 1.6 (Wang, 2001).

Table 3-7: A Next-Generation Toyota Camry

Engine	Emissions Performance	
6-cylinder advanced stoichiometric GDI, variable valve control, and cylinder deactivation	Baseline heat-trapping gas emissions Improved heat-trapping gas emissions % reduction	334 g CO_2-eq/mi 197 g CO_2-eq/mi 41%
Transmission	**Lifetime Impact**	
6-speed dual-clutch transmission without torque converter	Heat-trapping gas emissions reduced	42 tons
Vehicle	**Performance**	
C_d reduced 10% C_r reduced 20% Improved accessories Idle off	0 to 60 acceleration	8.9 sec
Air Conditioning	**Cost**	
HFC-152a system	Retail price increase Payback time	$1,960 4.8 years

NOTE: Mileage estimates from EMFAC 2002 (CARB, no date). Assumptions are a 16-year vehicle lifetime, a gasoline price of $1.68/gallon, and a real discount rate of 5%. Lifetime heat-trapping emission reductions are estimated using the well-to-wheels emission factor for California reformulated gasoline from GREET 1.6 (Wang, 2001).

vehicles and eliminate emissions associated with idling. Replacing HFC-134a with an alternative refrigerant that has a lower global warming potential will also be possible.

Applying these modifications to a Ford Explorer, as shown in Table 3-6, results in more than a 40 percent reduction in heat-trapping emissions from the base vehicle while maintaining vehicle performance and utility. The additional technology would add less than $2,000 to the price of a new Explorer, but these costs would be made up in little more than three years of driving the vehicle. Table 3-7 shows that a similar package applied to the Toyota Camry would result in a 41 percent reduction in heat-trapping emissions from the base vehicle, for approximately the same additional cost as the Explorer. These costs could be made up in less than five years of operation.

Impact of Statewide Changes

The emission reductions achieved in our case studies are not limited to the Toyota Camry and Ford Explorer. Table 3-8 shows the results of applying the relevant technologies across all five vehicle classes.

As mentioned earlier, applying currently available technology to all new cars sold in California could result in a 20 percent fleet average

Table 3-8: A Clean, Green Fleet

		Small Car	Large Car	Minivan	SUV	Pickup	Fleet Average
		Ford Focus	Toyota Camry	Dodge Grand Caravan	Ford Explorer	Chevrolet Silverado 1500 (extended cab)	
Baseline	Heat-trapping gas emissions (g CO_2-eq/mi)	292.9	334.2	368.6	440.0	487.1	361.3
Today's Technology	Heat-trapping gas emissions (g CO_2-eq/mi)	240.6	270.8	303.3	333.7	383.2	289.3
	% improvement	18%	19%	18%	24%	21%	20%
	Lifetime heat-trapping gas emissions reduced (tons)	13	16	16	29	27	18
	Cost of improvement	$495	$620	$620	$620	$700	$590
	Payback time (years)	3.8	3.9	3.8	1.9	2.3	3.2
Advanced Technology	Heat-trapping gas emissions (g CO_2-eq/mi)	178.3	196.8	234.7	251.3	297.3	216.9
	% improvement	39%	41%	36%	43%	39%	40%
	Lifetime heat-trapping gas emissions reduced (tons)	35	42	40	57	57	45
	Cost of improvement	$1,710	$1,960	$1,960	$1,960	$2,135	$1,904
	Payback time (years)	5.2	4.8	5.1	3.2	3.5	4.4

NOTE: Mileage estimates from EMFAC 2002 (CARB, no date). Assumptions are a 16-year vehicle lifetime, a gasoline price of $1.68/gallon, and a real discount rate of 5%. Lifetime heat-trapping emission reductions are estimated using the well-to-wheels emission factor for California reformulated gasoline from GREET 1.6 (Wang, 2001).

reduction in heat-trapping emissions. The additional cost of that technology would be made up, on average, in little more than three years of driving these vehicles—a shorter amount of time than the typical auto loan.

Applying our advanced technology package to all new vehicles sold in California would result in a 40 percent reduction in heat-trapping emissions, and the additional costs associated with the technological improvements would be recouped in less than four and a half years of driving. While we did not simulate HEVs in this analysis, application of previous results suggests that new, advanced-technology HEVs will produce 60 percent fewer heat-trapping emissions (Friedman, 2003).

Making the Clean, Green Fleet a Reality

Setting California on the path to cooler cars requires consideration of the technical and economic aspects of vehicle equipment and design changes. Some changes that would reduce heat-trapping emissions can happen in a relatively short timeframe (e.g., low-leak air conditioning and some vehicle load reduction strategies). Others, such as engine and transmission modifications, require a major platform redesign. And since the time between major redesigns, which varies by manufacturer and model, is in the range of four to six years (Ward's Communications, 2004; Tennant and Roberts, 2001), near-term emission reduction goals need to factor in these constraints.

That being said, ongoing innovation by automakers and penetration of new technologies will enable California to forge multiple paths to cleaner vehicles. More advanced technologies such as dual-clutch transmissions, for example, are expected to appear on more vehicles in the next few years, enhancing the emission reductions possible with today's technology.[5] In addition, the market share of HEVs is predicted to rise to three percent of the national new car fleet by 2009 (J.D. Power, 2003). Assuming that one-quarter of these vehicles are sold in California, they could comprise 10 percent of the state's new vehicle fleet by the end of the decade. GM, Ford, Toyota, and Honda have all announced plans to introduce more hybrid models, including SUVs and large cars, which would help increase the market appeal of HEVs and the potential to fully realize their heat-trapping emission reduction benefits.

Achieving emission reductions in the near term is a crucial first step toward long-term heat-trapping emission stability. But this is just the start of the path to the much larger emission reductions possible within the framework of California's Vehicle Global Warming Law. Coupling near-term goals that realize existing potential with more ambitious emission reductions is necessary to ensure that environmental performance gains made by the state's passenger vehicle fleet are not overtaken by increases in vehicle population and vehicle miles traveled. A vision that extends from today into the next decade will keep California on the road to climate-friendly vehicles.

[5] A dual-clutch transmission is already available on the Audi TT.

Chapter 4

The Benefits of a Clean, Green Fleet in California and Beyond

Benefits for California's Drivers and Environment

Motor vehicles are California's largest contributor to local and global air pollution. On average, each MY 2000 passenger vehicle sold in California released more than eight tons of CO_2 into the atmosphere during its first year on the road. Along with each ton of CO_2, the distribution and combustion of gasoline produce pounds of toxics and PM, along with HCs and NOx—the compounds that contribute to the formation of ozone, the primary component of urban smog.

A future new vehicle fleet that achieves a 40 percent reduction in heat-trapping emissions would eliminate nearly 25 tons of benzene-equivalent toxic emissions over the vehicles' lifetime. Nearly 3,000 tons of HCs and NOx would also be eliminated.

In addition to these environmental benefits, the proposed technological improvements would provide California consumers with significant economic savings over the lifetime of their vehicles. Vehicles that meet the emissions performance demonstrated by our package of currently available technology could save California drivers as a whole more than $2.5 billion in lifetime operating costs. A fleet that matches the environmental performance demonstrated with our advanced technology package could save California drivers more than $6.5 billion. These savings will be even larger in the future as the state's vehicle population and miles traveled continue to increase. Furthermore, given the volatile nature of gasoline prices in California, these savings will grow larger still if gasoline price spikes persist.

Benefits Beyond California

Just as the impact of climate change is not confined by California's borders, the regulations established under the state's Vehicle Global Warming Law could have an impact felt far outside its borders. Since California accounts for approximately 10 percent of new vehicles sold in the United States, controlling the emissions released by vehicles sold in the state will have an important effect on mobile-source heat-trapping emissions nationwide.

Equally important is the example California sets for the rest of the nation. Ideally, the state's emission standards will become a model for a federal program to reduce heat-trapping emissions from passenger vehicles. At the very least, these regulations could be replicated by other states in the near term.

Western States

One potential starting point for the spread of California regulations is the agreement between the governors of California, Oregon, and Washington to take regional action against global warming (Office of the Governors, 2003).[6] Regional policies to reduce heat-trapping emissions could include adoption of regulations established under California's Vehicle Global Warming Law across the entire region, which would

[6] The agreement was announced during the administration of California Governor Gray Davis, but Governor Arnold Schwarzenegger has pledged his support since taking office.

encompass almost 15 percent of all vehicles sold in the United States (Ward's Communications, 2003).[7] The effect of such regulations could be even greater if these states invite other western states and Canadian provinces to join the agreement.

New England and Mid-Atlantic States

Connecticut, Delaware, Maine, Massachusetts, New Hampshire, New Jersey, New York, Rhode Island, and Vermont have also established a cooperative, regional agreement to reduce heat-trapping emissions called the Regional Greenhouse Gas Initiative (RGGI). Several other states and Canadian provinces are participating as observers, and some of the RGGI states—Maine, Massachusetts, New York, New Jersey and Vermont—have already adopted California's LEV program. Adoption by the RGGI states of the regulations established under California's Vehicle Global Warming Law would encompass approximately one-quarter of all vehicles sold in the United States.

Canada

The cumulative impact of western and RGGI states adopting vehicle global warming regulations similar to California could affect approximately 30 percent of the nation's new vehicle sales. Canada, in addition to observing the RGGI and western states agreements, has expressed its desire to adopt California's vehicle global warming regulations as well.[8] That development would bring one million more vehicles onto the path toward climate-friendly transportation (Ward's Communications, 2003a).

California's Climate Goals

Reducing heat-trapping emissions from motor vehicles in California is a crucial first step to mitigating the overall impact of global warming. California faces serious environmental, economic, and public health risks as a result of the changing climate, but our modeling demonstrates that the technological means to significantly reduce emissions exists today. And, technologies right on the horizon promise even greater reductions.

California has assumed the role of a national leader on climate change policy and has the opportunity to realize the significant technological potential currently available to reduce heat-trapping emissions from its passenger vehicle fleet. Implementing a near-term emission standard that realizes this potential, followed by a series of stringent, forward-looking reduction targets, will get California off the current trajectory of ever-increasing heat-trapping emissions.

As in the past, marrying the innovation of the auto industry with the authority of government regulations will lead to major advances in the environmental friendliness of the passenger vehicle fleet (Clark et al., 2003; Johnson, 1999). The California Vehicle Global Warming Law sets an important regulatory example for other states and nations to follow, and the ripple effect will have a significant impact on heat-trapping emissions well beyond the state's borders.

[7] All calculations for the influence of California's Vehicle Global Warming Law are based on registration data from Ward's Communications (2003a).

[8] Canadian Minister of the Environment David Anderson stated in a speech on March 11, 2004, that Canada would like to join with progressive U.S. states to create the "critical mass" needed for climate-friendly vehicles.

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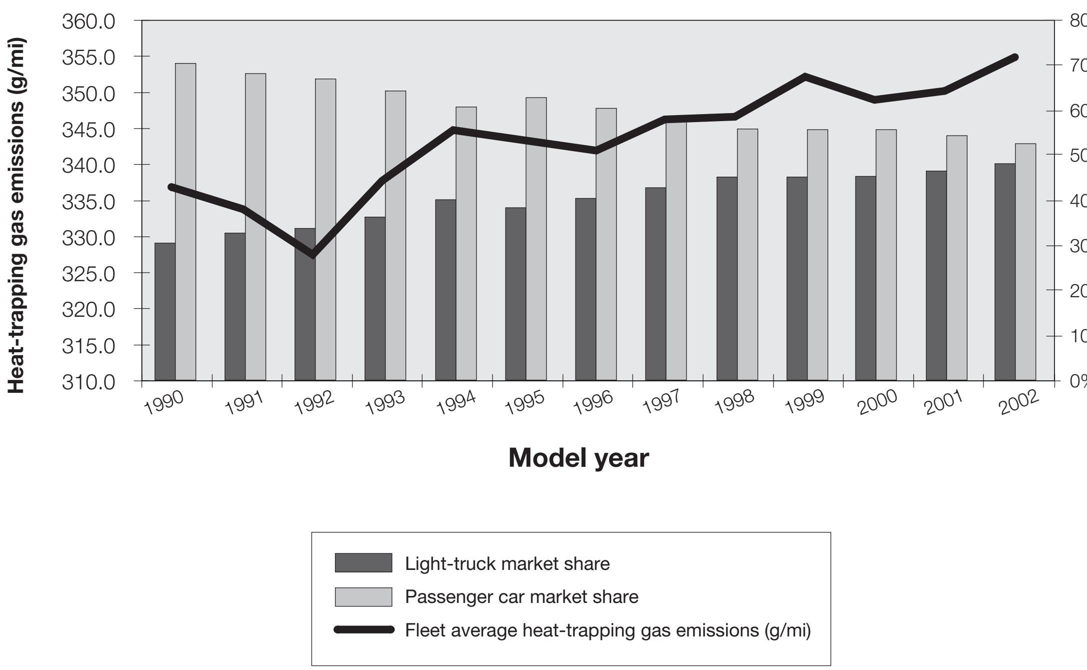
Appendix A

Impact of Vehicle Sales and Performance on Emission Reductions

Shifts in the vehicle market, such as the growth of light trucks (shown in Figure A-1), have had an obvious impact on the environmental performance of the vehicle fleet. Competition between manufacturers to build more powerful and aggressive vehicles also slows the path to cleaner vehicles. This is often used as an argument by automakers reluctant to improve the environmental performance of their vehicle fleets. However, building climate- and consumer-friendly vehicles is not an either-or proposition. The fact is that we can do both.

In order to understand the impact of these trends on our potential to reduce global warming pollution from the vehicle fleet, the Union of Concerned Scientists performed sensitivity analyses using our technology packages and modeling results. Using altered vehicle market mixes and more aggressive performance levels, we estimated emission reduction potential from our moderate

Figure A-1: **Trend in Light-Truck Sales and Heat-Trapping Emissions**



SOURCE: Hellman and Heavenrich, 2003.

and advanced technology packages under several potential MY 2009 scenarios.

The first scenario we examined is increased penetration of light trucks into the vehicle market. Using Environmental Protection Agency (EPA) vehicle trends data, we extrapolated the potential and projected that light trucks will comprise 59 percent of new vehicle sales in 2009 (Heavenrich and Hellman, 2003). We assumed that this increase would displace large cars and that the proportion of vans, light trucks, and SUVs would remain the same. Using these revised market shares, we recalculated potential emission reductions using our modeled simulations (Scenario A).

Much like the rise in popularity of SUVs in the early 1990s, crossover vehicles (XUVs) have increased in popularity in recent years, claiming a greater share of light-truck sales. By definition, XUVs such as the Saturn Vue, Nissan Murano, and Chrysler Pacifica defy simple classification because they combine the features of two or more vehicle classes (e.g., the features of an SUV with the drivability and construction of a car). XUVs also generally have lower emissions than comparable SUVs. The impact of increasing XUV sales is less certain than that of light-truck sales; depending on whether XUVs replace SUVs or cars, they can have either a positive or negative impact on environmental performance.

In order to estimate the impact of growing XUV sales on potential emission reductions, we applied our technology packages to the Saturn Vue. Looking at current sales, we added the modeling results for the Saturn Vue into our fleet mix and assumed XUVs would acquire 15 percent of the market by 2009, a conservative estimate based on figures from Visnic (2003). We analyzed the impact of this growth for two scenarios: XUVs replacing large cars (Scenario B) and XUVs replacing SUVs (Scenario C).

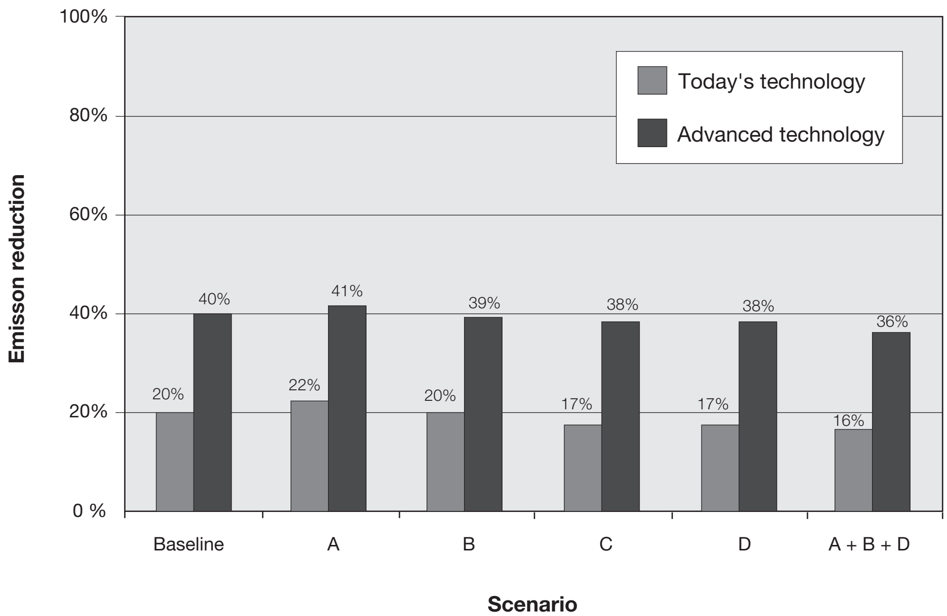
In the fourth scenario, we estimated the reduction in emission reduction potential if vehicle performance continues to increase at current rates. Using EPA trends data, we extrapolated performance levels for MY 2009 vehicles in each vehicle class. We then estimated the emission reduction potential of our technology packages using new model simulations adjusted so that vehicles meet our projected 2009 performance levels (Scenario D).

Since it is unlikely that any one of these trends will occur in isolation, we also include a potential worst-case scenario in which light-truck

Table A-1: **Sensitivity Analysis Scenarios**

Scenario	Description
A	Light-truck sales growth continues unabated and reaches 59% of all vehicle sales (assuming the proportion of trucks, vans, and pickups is the same as in 2002)
B	Crossover sales reach 15% of the vehicle market and replace all large cars
C	Crossover sales reach 15% of the vehicle market and replace all SUVs
D	Vehicle performance growth continues unabated and reaches projected 2009 levels
A + B + D	Worst case: Vehicle performance and light-truck sales increase unabated and crossover sales replace all large cars

Figure A-2: **Sensitvity Analysis Results**



sales continue to grow, XUVs make up 15 percent of the fleet and replace large cars exclusively, and performance continues to increase at current rates (Scenario A+B+D).

As Figure A-2 shows, shifts in the market do not dramatically diminish the potential for emission reductions when they happen in isolation. Increasing sales of XUVs as replacements for SUVs can lead to slightly larger emission reductions because XUVs tend to be lower-emitting than the SUVs they replace. Therefore, when they replace cars, we could see a slight dip in the emission reduction potential, as in our advanced technology case in Scenario B. Of the individual scenarios, the increased penetration of light trucks has the largest negative impact on emission reductions. But, because emission reductions are possible across the vehicle fleet and there is more opportunity for emission reductions in the light-truck market due to lower rates of technology penetration, the emission reduction potential remains significant.

Even Scenario D, in which performance increases unabated, fleet average emission reductions total 17 and 38 percent for our two technology packages. Some improvements that focus on engine specific power (hp/L) are eroded when these are used to boost vehicle performance rather than reduce emissions (i.e., the engine is not downsized when specific power is increased). However, because the environmental benefits of other technological improvements such as cylinder deactivation and idle-off are also dependent on driving conditions, the emission reduction potential for these technologies is not eroded as substantially by boosts in vehicle power.

These individual analyses represent only a few possibilities of what might happen in the future. Naturally, there is uncertainty predicting the direction that the market will go and whether vehicle performance trends will continue at current rates. In reality, it is likely that each of these trends will continue to some degree. A potential worst-case scenario in which XUVs replace large cars exclusively, light-truck sales grow unabated, and vehicle performance continues to increase at current rates would lead to the largest decrease in emission reduction potential. But, even in this case, the potential for emission reductions remains at 16 and 36 percent for our two packages.

An important lesson emerges from this analysis. Changes in vehicle mix and performance do not have to come at the expense of environmental performance. The technology exists to build cleaner vehicles that meet varying consumer demands and market preferences across all vehicle classes. The market, consumers, and the environment do not need to be at odds with one another.

Appendix B
Methodology

Non-CO_2 Emissions Estimates

Tailpipe emissions of CH_4 and N_2O were assumed to correlate with non-methane organic gas (NMOG) and NOx emissions, respectively (Lipman and Delucchi, 2002). Using N_2O and CH_4 emissions estimates from the California Energy Commission's GHG Emission Inventory, we regressed CH_4 emissions data onto NMOG emission standards and N_2O emissions onto emission standards (CEC, 2002). Given the current NMOG fleet average requirements under LEV II, we assumed that the average vehicle would meet ULEV II tailpipe standards. We then used these standards to predict CH_4 and N_2O emissions. Table B-1 shows the data used to predict these relationships.

Figures B-1 and B-2 show the relationships between the variables.

Table B-1: **Emissions Data Used to Project N_2O and CH_4 Emissions**

Vehicle Type	NOx Standard (g/mi)	N_2O (g/mi)	NMOG Standard (g/mi)	CH_4 (g/mi)
LEV PC	0.2	0.028	0.075	0.040
Tier 1 PC	0.4	0.046	0.250	0.048
Tier 0 PC	1.0	0.081	0.340	0.064
ULEV II PC/LT	0.07	***0.022***	0.055	***0.037***

NOTE: Values in bold italics are based on regression.
SOURCE: LEV, Tier 1, and Tier 0 data from CEC, 2002.

Figure B-1: **CH_4 and NMOG Relationship**

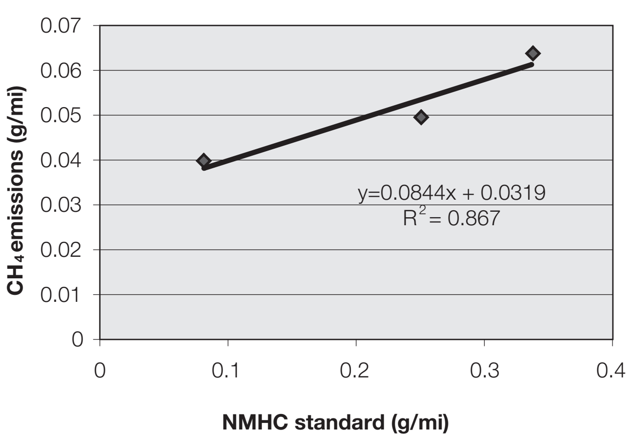


Figure B-2: **N_2O and NOx Relationship**

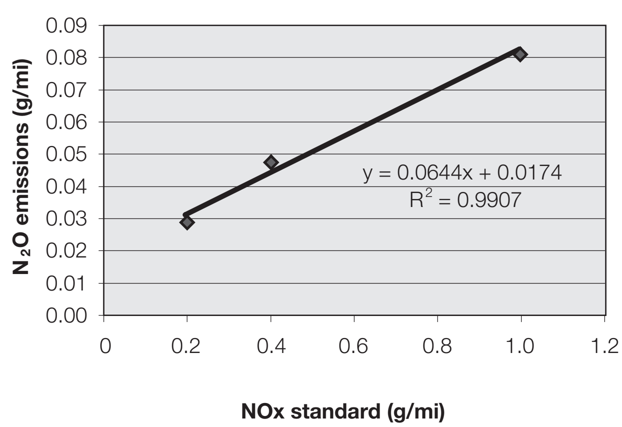


Table B-2: **Values Used to Estimate Direct Refrigerant Emissions**

Source of Direct Emissions	
Controlled leakage	57 g/year
Uncontrolled leakage	14 g/year
Emissions during service	45 g/service
Assumptions	
Annual mileage	15,000
Service rate	2 per lifetime
Vehicle lifetime	16 years

Calculated Emissions (g/mi)	
Including service emissions	5.108 x 10^{-3}
Excluding service emissions	4.733 x 10^{-3}
Calculated Emissions (g CO_2-eq/mi)	
Including service emissions	6.6
Excluding service emissions	6.2

SOURCE: Bhatti, 1998 and Vainio, 2003.

Table B-3: **Emission Factors for California Reformulated Gasoline**

Ozone Precursors		Toxics				Heat-Trapping Gases	
	g/gal		mg/gal	unit risk factor ($\mu g/m^3$)$^{-1}$	mg benzene-eq/gal		g/gal
NOx	0.0366	Benzene	4.82	2.9 x 10^{-5}	4.82	Upstream	8,467
NMOG	0.5690	1,3-butadiene	0.01	1.7 x 10^{-4}	0.06	Tailpipe	2,419
		Formaldehyde	0.88	6 x 10^{-6}	0.18	Total	10,886
		Acetaldehyde	0.44	2.7 x 10^{-6}	0.04		

SOURCE: Heat-trapping gases from GREET 1.6 (Wang, 2001); ozone precursors and toxics provided by Stephan Unnasch.

Direct Refrigerant Emissions

Estimates of direct refrigerant emissions were assumed to be uniform across the fleet. Values for leakage rates from Bhatti (1998) and Vainio (2003) were used to estimate emission rates in grams per mile. The assumptions are shown in Table B-2. A value of 6.6 g CO_2-eq/mi was used in our calculations.

Upstream and Fuel Cycle Emissions

Upstream emissions of heat-trapping gases associated with California reformulated gasoline were calculated using Argonne National Laboratory's Greenhouse Gas, Regulated Emissions, and Energy Use in Transportation Model (GREET). Given the global nature of heat-trapping emissions, these factors account for emissions worldwide. Toxic and criteria pollutant emission factors are based on analysis of marginal emissions, that is, emissions within the state of California (personal communication with Unnasch, 2004). Emission factors for toxics are expressed as mg of benzene-equivalent, using a unit risk factor for benzene of 2.9 x 10^{-5} ($\mu g/m^3$)$^{-1}$ (CARB, 2003).

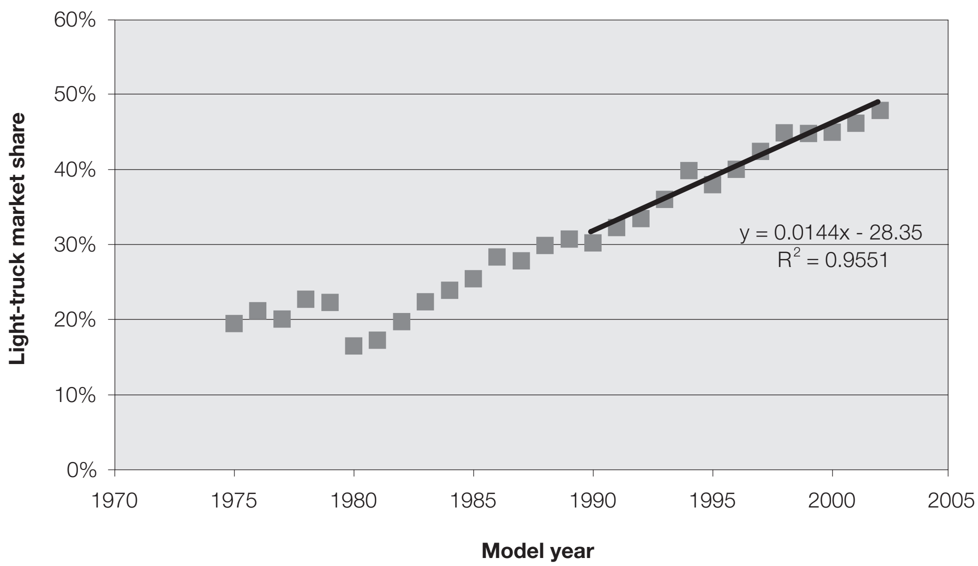
GREET 1.6 was also used to predict heat-trapping emissions from alternative-fuel vehicles. The results shown here are based on long-term (2012 and beyond) assumptions for passenger cars in California.

Table B-4: **Emission Factors for Alternative-Fuel Vehicles**

	Heat-Trapping Gas Emissions (g CO_2-eq/mi)			
Fuel	Feedstock	Fuel	Vehicle	WTW
Compressed natural gas	38	18	243	299
E90 (corn feedstock)	-159	140	299	280
Gaseous H_2 (North American natural gas)	10	171	0	181
E90 (biomass feedstock)	-253	27	299	73
Gaseous H_2 (solar electrolysis)	0	22	0	22

SOURCE: GREET 1.6 (Wang, 2001).

Figure B-3: **Trend in Light-Truck Market Share**



NOTE: Regression based on data from 1990 to 2002.
SOURCE: Hellman and Heavenrich, 2003.

Sensitivity Analysis

Data for each of the sensitivity analysis scenarios, with the exception of crossover vehicle market penetration, were collected from Hellman and Heavenrich (2003). Projections were based on changes since MY 1990 and included data up to MY 2002. We selected MY 1990 because vehicle regulations have been fairly constant during that timeframe. The projections are based on the linear regressions presented above.

Light Trucks

Light trucks have comprised an increasingly large share of the vehicle market over the past 15 years and their popularity shows no sign of abating. We projected the increase of total light-truck sales and assumed that the proportion of SUVs, pickup trucks, and vans would remain the same. Figure B-3 shows the trends used to predict 2009 market share.

Vehicle Performance

Over the past 10 years, engine power has steadily increased for all vehicle classes. Much of this increased power has come through engineering improvements as demonstrated by the steady increase in engine specific power (the ratio of engine power per unit volume). Rather than being applied to vehicle emission reduction, these advances have been applied to vehicle performance increases, as evidenced in the steady trend toward faster acceleration rates among all vehicle classes.

The EPA calculates 0 to 60 time based on a vehicle's horsepower-to-weight (hp/weight) ratio. For each vehicle class, we used EPA trends data to project hp/weight ratios in 2009 (Hellman and Heavenrich, 2003). Then, without changing vehicle weight, we repeated our technology improvement simulations, this time requiring that each vehicle meet this new hp/weight ratio.

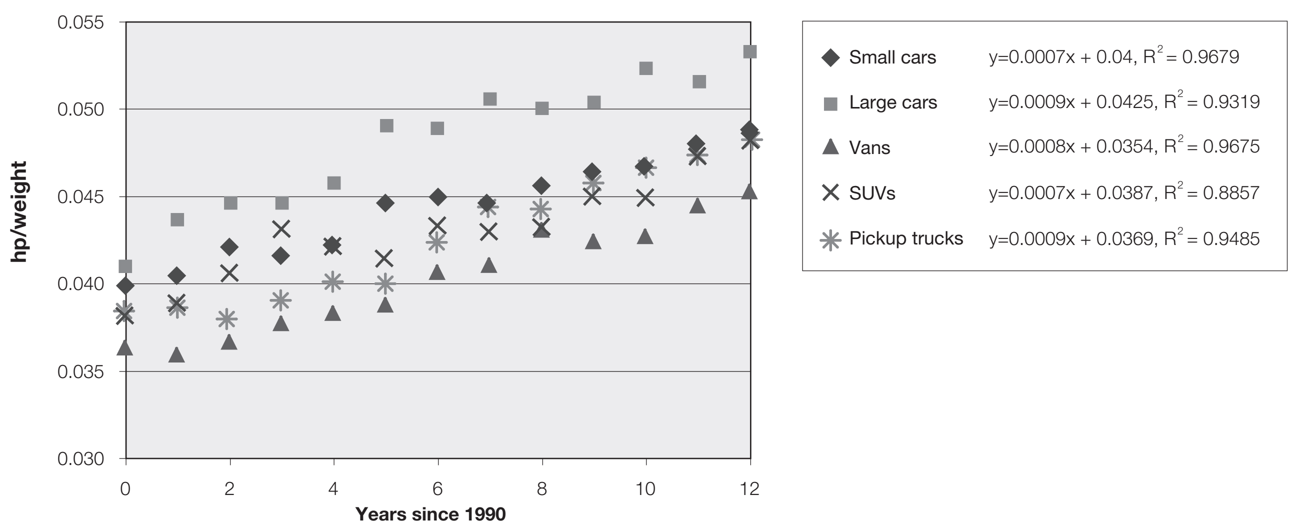
Crossover Vehicles

In addition to the five vehicles discussed in the body of this report, we also simulated technology improvements in the Saturn Vue, which would represent the crossover vehicle class for the purpose of our sensitivity analysis. Table B-5 shows the modeling results for the Saturn Vue.

Technology Package Pricing

Retail price increases associated with each technological improvement are shown in Table B-6. Our estimates were based on Plotkin et al. (2002), and engine technology improvements were scaled according to the number of cylinders.

Figure B-4: **Trends in Vehicle Horsepower-to-Weight Ratios**



SOURCE: Hellman and Heavenrich, 2003.

Table B-5: MEEM Results for the Saturn Vue

Baseline	Heat-trapping gas emissions (g CO_2-eq/mi)	351.0
Today's Technology	Heat-trapping gas emissions (g CO_2-eq/mi)	277.5
	% improvement	21%
	Cost of improvement	$620
	Payback time (years)	4.1
Advanced Technology	Heat-trapping gas emissions (g CO_2-eq/mi)	219.8
	% improvement	37%
	Cost of improvement	$1,960
	Payback time (years)	4.6

Table B-6: Technology Cost Estimates

	Small Car	Large Car	Minivan	SUV	Pickup	Crossover
Moderate Package						
Aerodynamic drag reduction	$35	$35	$35	$35	$35	$35
Rolling resistance reduction	$20	$20	$20	$20	$20	$20
Improved engine	$275	$300	$300	$300	$360	$300
Transmission	$115	$115	$115	$115	$115	$115
Cylinder deactivation	n/a	$100	$100	$100	$120	$100
Enhanced air conditioning system (134a)	$50	$50	$50	$50	$50	$50
Total	**$495**	**$620**	**$620**	**$620**	**$700**	**$620**
Advanced Package						
Further aerodynamic drag reduction	$95	$95	$95	$95	$95	$95
Further rolling resistance reduction	$50	$50	$50	$50	$50	$50
Stoichiometric GDI	$380	$500	$500	$500	$620	$500
Transmission	$0	$0	$0	$0	$0	$0
Cylinder deactivation	n/a	$100	$100	$100	$120	$100
42V ISG	$1,050	$1,050	$1,050	$1,050	$1,050	$1,050
Accessory improvement	$85	$115	$115	$115	$150	$115
HFC-152a air conditioning system	$50	$50	$50	$50	$50	$50
Total	**$1,710**	**$1,960**	**$1,960**	**$1,960**	**$2,135**	**$1,960**

Appendix C
Detailed Vehicle Data

Table C-1: **Baseline Vehicles**

		Small Car	Large Car	Minivan	SUV	Pickup	Crossover
		2004 Ford Focus	2003 Toyota Camry	2003 Dodge Grand Caravan	2003 Ford Explorer	2004 Chevrolet Silverado 1500 (extended cab)	2003 Saturn Vue
		ZTS 4-door sedan	SE 4-door sedan (3.0L 6-cylinder 4A)	ES FWD 4-door minivan (3.8L 6-cylinder 4A)	XLT 4WD 4-door SUV (4.0L 6-cylinder 5A)	LS RWD 4-door (4.8L 8-cylinder 4A)	AWD 4-door SUV (3.0L 6-cylinder 5A)
Vehicle Characteristics	C_d	0.36	0.30	0.40	0.45	0.45	0.41
	C_r	0.010	0.009	0.010	0.011	0.011	0.011
	Curb weight (lbs)	2,715	3,351	4,258	4,159	4,555	3,491
Engine Characteristics	Type	DOHC I4	DOHC V6	OHV V6	SOHC V6	OHV V8	DOHC V6
	Valves per cylinder	4	4	2	2	2	4
	Peak horsepower (hp)	144	192	215	210	285	181
	hp/weight	0.053	0.057	0.050	0.050	0.063	0.052
	RPM at peak hp	5,750	5,300	5,000	5,100	5,600	6,000
	Peak torque (lb-ft)	149	209	245	254	295	195
	RPM at peak torque	4,200	4,400	4,000	3,700	4,000	4,000
	Size (L)	2.3	3	3.8	4	4.8	3
	hp/L	62.6	64.0	56.6	52.5	59.4	60.3
Transmission	Type	4A	4A	4A	5A	4A	5A
Vehicle Performance	0 to 60 time	9.3	8.7	10.2	9.2	9.8	8.8
	0 to 30 time towing 1,500 lbs				4.7	4.8	
Heat-Trapping Gas Emissions ($g\ CO_2$-eq/mi)	CO_2	266.4	306.0	338.9	407.2	452.2	322.0
	Indirect CO_2	12.1	13.9	15.4	18.5	20.6	14.7
	Direct HFC-134a	6.7	6.7	6.7	6.7	6.7	6.7
	CH_4	0.8	0.8	0.8	0.8	0.8	0.8
	N_2O	6.8	6.8	6.8	6.8	6.8	6.8
	Total	**292.9**	**334.2**	**368.6**	**440.0**	**487.1**	**351.0**

SOURCE: *Consumer Reports* and Edmunds.com.

Table C-2: **Today's Technology Modeling Results (2003 Performance Level)**

		Small Car	Large Car	Minivan	SUV	Pickup	Crossover
		2004 Ford Focus	2003 Toyota Camry	2003 Dodge Grand Caravan	2003 Ford Explorer	2004 Chevrolet Silverado 1500 (extended cab)	2003 Saturn Vue
		ZTS 4-door sedan	SE 4-door sedan (3.0L 6-cylinder 4A)	ES FWD 4-door minivan (3.8L 6-cylinder 4A)	XLT 4WD 4-door SUV (4.0L 6-cylinder 5A)	LS RWD 4-door (4.8L 8-cylinder 4A)	AWD 4-door SUV (3.0L0 6-cylinder 5A)
Vehicle Characteristics	C_d	0.288	0.29	0.36	0.41	0.41	0.37
	C_r	0.009	0.008	0.009	0.010	0.010	0.010
	Curb weight (lbs)	2,715	3,351	4,258	4,159	4,555	3,491
Engine Characteristics	Type	4-cylinder VVLT	6-cylinder VVLT, cylinder deactivation	6-cylinder VVLT, cylinder deactivation	6-cylinder VVLT, cylinder deactivation	8-cylinder VVLT, cylinder deactivation	6-cylinder VVLT, cylinder deactivation
	Valves per cylinder	4	4	4	4	4	4
	Peak hp	157	207	215	235	295	210
	hp/weight	0.058	0.062	0.050	0.057	0.065	0.060
	RPM at peak hp	6,250	6,250	6,250	6,250	6,250	6,250
	Peak torque (lb-ft)	139	183	190	208	261	186
	RPM at peak torque	5,000	5,000	5,000	5,000	5,000	5,000
	Size (L)	2.0	2.6	2.7	2.9	3.7	2.6
	hp/L	80.0	80.0	80.0	80.0	80.0	80.0
Transmission	Type	CVT	6A	6A	6A	6A	6A
Vehicle Performance	0 to 60 time	9.3	8.7	10.2	9.3	9.1	8.8
	0 to 60 time towing 1,500 lbs				11.6	10.4	
	0 to 30 time towing 1,500 lbs				4.8	4.8	
Heat-Trapping Gas Emissions (g CO_2-eq/mi)	CO_2	222.1	251.2	282.7	312.1	360.0	265.1
	Indirect CO_2	7.6	8.6	9.6	10.7	12.3	9.0
	Direct HFC-134a	3.4	3.4	3.4	3.4	3.4	3.4
	CH_4	0.8	0.8	0.8	0.8	0.8	0.8
	N_2O	6.8	6.8	6.8	6.8	6.8	6.8
	Total	**240.6**	**270.8**	**303.3**	**333.7**	**383.2**	**285.1**

SOURCE: *Consumer Reports* and Edmunds.com.

Table C-3: **Advanced Technology Modeling Results (2003 Performance Level)**

		Small Car	Large Car	Minivan	SUV	Pickup	Crossover
		2004 Ford Focus	2003 Toyota Camry	2003 Dodge Grand Caravan	2003 Ford Explorer	2004 Chevrolet Silverado 1500 (extended cab)	2003 Saturn Vue
		ZTS 4-door sedan	SE 4-door sedan (3.0L 6-cylinder 4A)	ES FWD 4-door minivan (3.8L 6-cylinder 4A)	XLT 4WD 4-door SUV (4.0L 6-cylinder 5A)	LS RWD 4-door (4.8L 8-cylinder 4A)	AWD 4-door SUV (3.0L0 6-cylinder 5A)
Vehicle Characteristics	C_d	0.26	0.26	0.32	0.36	0.36	0.33
	C_r	0.008	0.007	0.008	0.009	0.009	0.009
	Curb weight (lbs)	2,715	3,351	4,258	4,159	4,555	3,491
Engine Characteristics	Type	4-cylinder GDI, VVLT	6-cylinder GDI, VVLT, cylinder deactivation	6-cylinder GDI, VVLT, cylinder deactivation	6-cylinder GDI, VVLT, cylinder deactivation	8-cylinder GDI, VVLT, cylinder deactivation	6-cylinder GDI, VVLT, cylinder deactivation
	Valves per cylinder	4	4	4	4	4	4
	Peak hp	155	190	215	230	285	205
	hp/weight	0.057	0.057	0.050	0.055	0.063	0.059
	RPM at peak hp	6,300	6,300	6,300	6,300	6,300	6,300
	Peak torque (lb-ft)	140	172	194	208	258	185
	RPM at peak torque	5,400	5,400	5,400	5,400	5,400	5,400
	Size (L)	1.9	2.4	2.7	2.9	3.6	2.6
	hp/L	79.9	79.9	79.9	79.9	79.9	79.9
Transmission	Type	CVT	DCT-6	DCT-6	DCT-6	DCT-6	DCT-6
Vehicle Performance	0 to 60 time	9.1	8.9	9.8	9.1	8.7	8.7
	0 to 60 time towing 1,500 lbs				11.4	9.9	
	0 to 30 time towing 1,500 lbs					4.4	
Heat-Trapping Gas Emissions (g CO_2-eq/mi)	CO_2	163.6	181.4	217.9	233.8	277.9	203.5
	Indirect CO_2	6.7	7.4	8.9	9.6	11.4	8.3
	Direct HFC-134a	0.3	0.3	0.3	0.3	0.3	0.3
	CH_4	0.8	0.8	0.8	0.8	0.8	0.8
	N_2O	6.8	6.8	6.8	6.8	6.8	6.8
	Total	**178.3**	**196.8**	**234.7**	**251.3**	**297.3**	**219.8**

SOURCE: *Consumer Reports* and Edmunds.com.

Table C-4: **Today's Technology Modeling Results (2009 Performance Level)**

		Small Car	Large Car	Minivan	SUV	Pickup	Crossover
		2004 Ford Focus	2003 Toyota Camry	2003 Dodge Grand Caravan	2003 Ford Explorer	2004 Chevrolet Silverado 1500 (extended cab)	2003 Saturn Vue
		ZTS 4-door sedan	SE 4-door sedan (3.0L 6-cylinder 4A)	ES FWD 4-door minivan (3.8L 6-cylinder 4A)	XLT 4WD 4-door SUV (4.0L 6-cylinder 5A)	LS RWD 4-door (4.8L 8-cylinder 4A)	AWD 4-door SUV (3.0L0 6-cylinder 5A)
Vehicle Characteristics	C_d	0.29	0.29	0.36	0.29	0.41	0.37
	C_r	0.009	0.008	0.009	0.008	0.010	0.010
	Curb weight (lbs)	2,715	3,351	4,258	4,159	4,555	3,491
Engine Characteristics	Type	4-cylinder VVLT	6-cylinder VVLT, cylinder deactivation	6-cylinder VVLT, cylinder deactivation	6-cylinder VVLT, cylinder deactivation	8-cylinder VVLT, cylinder deactivation	6-cylinder VVLT, cylinder deactivation
	Valves per cylinder	4	4	4	4	4	4
	Peak hp	171	232	241	251	330	229
	hp/weight	0.063	0.069	0.057	0.060	0.073	0.066
	RPM at peak hp	6,250	6,250	6,250	6,250	6,250	6,250
	Peak torque (lb-ft)	151	205	213	222	292	202
	RPM at peak torque	5,000	5,000	5,000	5,000	5,000	5,000
	Size (L)	2.1	2.9	3.0	3.1	4.1	2.9
	hp/L	80.0	80.0	80.0	80.0	80.0	80.0
Transmission	Type	CVT	6A	6A	6A	6A	6A
Vehicle Performance	0 to 60 time	8.5	7.7	9.1	8.7	8.2	8.1
Heat-Trapping Gas Emissions ($g\ CO_2$-eq/mi)	CO_2	230.0	263.1	292.6	320.5	374.9	272.9
	Indirect CO_2	7.6	8.6	9.6	10.7	12.3	9.0
	Direct HFC-134a	3.4	3.4	3.4	3.4	3.4	3.4
	CH_4	0.8	0.8	0.8	0.8	0.8	0.8
	N_2O	6.8	6.8	6.8	6.8	6.8	6.8
	Total	**248.5**	**282.6**	**313.2**	**342.1**	**398.1**	**292.9**

SOURCE: *Consumer Reports* and Edmunds.com.

Table C-5: Advanced Technology Modeling Results (2009 Performance Level)

		Small Car	Large Car	Minivan	SUV	Pickup	Crossover
		2004 Ford Focus	2003 Toyota Camry	2003 Dodge Grand Caravan	2003 Ford Explorer	2004 Chevrolet Silverado 1500 (extended cab)	2003 Saturn Vue
		ZTS 4-door sedan	SE 4-door sedan (3.0L 6-cylinder 4A)	ES FWD 4-door minivan (3.8L 6-cylinder 4A)	XLT 4WD 4-door SUV (4.0L 6-cylinder 5A)	LS RWD 4-door (4.8L 8-cylinder 4A)	AWD 4-door SUV (3.0L0 6-cylinder 5A)
Vehicle Characteristics	C_d	0.26	0.26	0.32	0.36	0.36	0.33
	C_r	0.008	0.007	0.008	0.009	0.009	0.009
	Curb weight (lbs)	2,715	3,351	4,258	4,159	4,555	3,491
Engine Characteristics	Type	4-cylinder GDI, VVLT	6-cylinder GDI, VVLT, cylinder deactivation	6-cylinder GDI, VVLT, cylinder deactivation	6-cylinder GDI, VVLT, cylinder deactivation	8-cylinder GDI, VVLT, cylinder deactivation	6-cylinder GDI, VVLT, cylinder deactivation
	Valves per cylinder	4	4	4	4	4	4
	Peak hp	169	213	241	246	319	223
	hp/weight	0.062	0.064	0.057	0.059	0.070	0.064
	RPM at peak hp	6,300	6,300	6,300	6,300	6,300	6,300
	Peak torque (lb-ft)	153	192	218	223	289	202
	RPM at peak torque	5,400	5,400	5,400	5,400	5,400	5,400
	Size (L)	2.1	2.7	3.0	3.1	4.0	2.8
	hp/L	79.9	79.9	79.9	79.9	79.9	79.9
Transmission	Type	CVT	DCT-6	DCT-6	DCT-6	DCT-6	DCT-6
Vehicle Performance	0 to 60 time	8.3	8	8.8	8.4	7.8	8
Heat-Trapping Gas Emissions ($g\ CO_2$-eq/mi)	CO_2	168.5	187.1	223.5	237.6	286.7	207.7
	Indirect CO_2	6.7	7.4	8.9	9.6	11.4	8.3
	Direct HFC-134a	0.3	0.3	0.3	0.3	0.3	0.3
	CH_4	0.8	0.8	0.8	0.8	0.8	0.8
	N_2O	6.8	6.8	6.8	6.8	6.8	6.8
	Total	**183.1**	**202.5**	**240.3**	**255.1**	**306.0**	**223.9**

SOURCE: *Consumer Reports* and Edmunds.com.

Climate Control

Global Warming Solutions *for* California Cars

Global warming is the most serious long-term environmental threat facing California, the nation, and the world. The Golden State has assumed a leadership role in confronting this threat by focusing on the largest source of global warming pollution in the state: motor vehicles. Half of the heat-trapping gases that contribute to climate change in California are emitted by mobile sources, including cars, sport utility vehicles, and trucks, but significant technological potential exists to reduce these emissions.

This report provides an overview of the technologies that can immediately begin reducing the impact of California's vehicles on the global environment. For example, significant emission reductions are possible through vehicle load reduction and improvements in vehicle engines, transmissions, and air conditioning systems. Our analysis demonstrates that a 20 percent reduction in heat-trapping emissions from California's new vehicle fleet is possible with technologies that are available today. Even larger reductions will be possible as advanced technologies become available during the coming decade.

Realizing this technological potential will start California down the road to a clean, green vehicle fleet and will set an important example for other states and countries.

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