The Diesel Dilemma

Diesel's Role in the Race for Clean Cars

Union of Concerned Scientists
Citizens and Scientists for Environmental Solutions

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January 2004

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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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COVER ILLUSTRATION: Nathan Walker/NathanWalker.net
DESIGN: David Gerratt/NonprofitDesign.com

Printed on recycled paper

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Acknowledgments

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

The authors would like to thank Feng An for his fuel economy modeling and John DeCicco for his review of the technical findings and his expertise in these areas. Thanks also go to Julie Anderson, Louise Bedsworth, Rich Hayes, Jason Mark, Scott Nathanson, and Michelle Robinson for helpful comments, Bryan Wadsworth for editing, and David Gerratt for layout.

The opinions expressed in this report do not necessarily reflect the opinions of the foundations that supported the work. Both the opinions and the information contained herein are the sole responsibility of the authors.

Executive Summary

Increasing concerns over oil dependence and climate change have prompted renewed U.S. interest in diesel technology for cars and trucks despite a history of poor sales in the American market. Diesel also continues to carry the stigma of being a "dirty" fuel. This image has the potential to change as a result of new technology, but questions remain about how much cleaner diesel vehicles can get.

If emissions challenges can be overcome, diesel cars may be able to incorporate and compete with other fuel-saving technologies, such as more efficient engines, better transmissions, improved aerodynamics, and high-strength materials. Diesel will still carry a higher price tag, however.

Should Americans invest in diesel or gasoline cars and light trucks to reduce oil usage, global warming pollution, and toxic air contaminants—while saving money at the pump? The Union of Concerned Scientists (UCS) explored this question by comparing the cost, fuel economy, and emissions performance of conventional, advanced, and hybrid-electric diesel and gasoline cars (Table ES-1).

This report presents a new analysis of these fuel-saving technologies, applying each to the five major classes of passenger vehicles (small cars, larger "family" cars, sport utility vehicles, minivans, and pickup trucks). Our analysis provides an apples-to-apples comparison of diesel and gasoline by evaluating vehicles with equivalent 0 to 60 mph acceleration performance, assuming both fuels can meet the same air pollution emission levels within the new federal tailpipe standards, and accounting for the difference in energy content between the fuels.

Our major findings are:

1. Diesel is becoming much cleaner, but key questions and challenges remain. Diesel vehicles appear to be on track to meet the weakest, and possibly the average, federal emissions standards for the latter part of this decade. However, concerns about real-world emissions, long-term pollution reduction, and the importance of non-regulated emissions may create public health barriers and cloud diesel's future.

- *Diesel cleanup technologies are rapidly advancing, and more effective systems appear close to realization.* Emission controls for reducing particulate matter, or soot, are already being offered on

Table ES-1 **Comparing Gasoline and Diesel Vehicles at a Glance**[a]

	Diesel	Gasoline
Initial cost	-	o
Net consumer savings	+	+ +
Cost-effectiveness for oil reduction	+	+ +
Cost-effectiveness for global warming benefits	+	+ +
Infrastructure availability	-	+ +
Tested tailpipe pollution	-	+
In-use pollution[b]	- - ?	-
Extreme towing capability	+	o
Range	+	o
Maximum potential oil reduction	+	+
Maximum potential global warming benefits[c]	+ + ?	+

KEY:
"+" This vehicle type excels in this area.
"-" This vehicle type performs poorly in this area.
"o" This vehicle type performs adequately in this area.

NOTES:
a. Multiple marks indicate significantly superior or inferior performance.
b. Assuming diesel emission controls fail at the same rate as gasoline, resulting in higher in-use pollution.
c. If diesel soot proves to be an important heat-trapping gas and is difficult to control, the potential global warming benefits from diesel will be muted.

many European diesel cars. Properly functioning particulate traps can cut these emissions and toxicity to very low levels, but reducing smog-forming nitrogen oxides is proving more challenging. Significant technical, cost, infrastructure, and pollution challenges remain.

- *Cleanup technology must ensure that real-world emissions match tailpipe standards.* Routine deterioration with age, tampering with emission controls, improper maintenance, and poor engineering already lead to more tailpipe emissions from gasoline vehicles. Diesel vehicles, for similar reasons, may suffer from dramatically higher in-use emissions than certification values indicate, particularly when new pollution controls are first implemented.
- *Future diesel vehicles may not be as clean as today's best gasoline cars.* Today's diesel cars and trucks are major polluters, releasing substantially more toxic soot and smog-forming nitrogen oxides from the tailpipe than the average gasoline vehicle. New federal regulations coming into full effect in 2009 will hold diesel engines to the same set of tailpipe standards as gasoline cars and trucks, but the structure of these standards allows some cars to release two times more soot and nearly three times more nitrogen oxides than the average vehicle.

  While some conventional and hybrid-electric gasoline cars are already several times cleaner than the average vehicle under the new tailpipe standards, no diesel vehicles are currently capable of meeting even the average standards. If diesel cars are unable to meet progressively tighter emissions standards, future progress in protecting public health may stall.
- *Non-regulated tailpipe emissions from gasoline and diesel vehicles could pose significant public health threats.* The federal Tier 2 tailpipe emissions standards are based entirely on the mass of pollutants emitted from a vehicle, but particle size, number, and toxicity may also be important indicators of the public health threats posed by diesel and gasoline vehicles.

2. Gasoline vehicles are more cost-effective than diesel for reducing oil use and lowering global warming pollution. As shown in Table ES-1, more efficient gasoline and diesel vehicles could substantially improve fuel economy and save consumers money at the pump. Our modeling, though, suggests that the high up-front cost of diesel engines and emission controls allows improved gasoline vehicles to deliver energy security and global warming benefits at a lower cost.

- *Diesel's oil savings and global warming benefits are often oversold.* Low-sulfur diesel fuel is more oil- and carbon-intensive than reformulated gasoline; each gallon requires 25 percent more petroleum and results in 17 percent more emissions of heat-trapping gases.[1] Thus, the fuel economy improvement afforded by diesel does not provide equivalent reductions in oil use and heat-trapping gases.

  Diesel vehicles can help a car travel 30 to more than 40 percent farther on a gallon of diesel fuel. However, this advantage is only partly due to the higher efficiency of diesel engines, which offer a 15 to 25 percent improvement over gasoline. The remaining increase is due to the fact that diesel fuel contains 13 percent more energy than a gallon of gasoline. We present our fuel efficiency results using the standard analytical measure of miles per gallon of

1 UCS calculation, including fuel production and refining, from Wang, 2003.

gasoline equivalent (mpgge) to account for the different energy content of gasoline and diesel fuels.

- *Consumers can save more money with efficient gasoline vehicles.* The higher costs of efficient diesel and gasoline vehicles are more than offset by reductions in fuel costs, saving consumers between $400 and nearly $2,000 over a vehicle's useful life. However, as a result of their higher up-front costs, diesel vehicles prove less cost-effective than gasoline vehicles, saving consumers as much as $700 less for an equivalent improvement in fuel efficiency. Diesel vehicles do offer superior capabilities in extreme towing situations, which may be desirable for a subset of consumers.
- *Gasoline vehicles provide oil savings at a lower cost.* To achieve a 20 to 30 percent reduction in oil demand, the average diesel passenger vehicle will add 2.5 to greater than 4 times more in up-front costs ($1,700 to $1,800) than an equivalent gasoline vehicle. To achieve a 50 percent reduction in oil demand, the gap for diesel drops only slightly, to about $1,600 (or nearly two times the added cost for an equivalent gasoline vehicle).
- *Gasoline vehicles reduce global warming gases at a lower cost.* To achieve a 30 percent reduction in global warming pollution, the average diesel vehicle will add nearly 2.5 times more in up-front costs ($1,600) than an equivalent gasoline vehicle. To achieve a 50 percent reduction in global warming pollution, the gap for diesel narrows to $1,100 (or approximately 1.7 times the added cost for an equivalent gasoline vehicle).

Our recommendations are:

1. Protect public health. At a minimum, the federal government must refrain from weakening its new Tier 2 tailpipe emissions standards. These standards are expected to prevent as many as 4,300 deaths per year (EPA, 1999) and should not be compromised.

In addition, research is needed on the impact of particle size, number, and toxicity to determine whether Tier 2 standards protect human health sufficiently. Evaluating the adequacy of emissions standards will also require the monitoring of in-use vehicle pollution, especially during the first decade in which the Tier 2 program goes into effect. Finally, inspection and maintenance (I/M) programs, which can help reduce the gap between expected and real-world pollution, should be expanded to include diesel vehicles, particularly if diesel becomes more popular in the light-duty vehicle sector.

2. Promote energy security. To reduce oil use and promote energy security, the average fuel economy of new vehicles must be increased. One method, raising the Corporate Average Fuel Economy (CAFE) standards, will ensure that consumers are offered a wide variety of fuel-efficient vehicle choices, but these standards need to be modified to eliminate inequities in the treatment of gasoline and diesel vehicles. Since CAFE gives credit to vehicles based on fuel economy rather than oil use, and a gallon of low-sulfur diesel fuel requires 25 percent more oil than a gallon of low-sulfur reformulated gasoline, putting more diesel vehicles on the road could actually increase U.S. oil dependence. CAFE standards should, at a minimum, compare gasoline and diesel on an energy-equivalent basis.

3. Avoid unnecessary tradeoffs. Protecting public health and improving vehicle fuel economy can and must be complementary goals. Performance-based incentives that focus on conventional technology can include diesel engines, but must also provide the same benefits to other conventional vehicle technologies and must reward higher fuel economy or lower heat-trapping gas emissions while also requiring lower tailpipe emissions than the average new car. Additional support for hybrid vehicles is merited given their link to a potential clean hydrogen fuel cell vehicle future. In addition, the United States should not follow Europe's lead by giving diesel tax advantages over gasoline or by creating new emissions loopholes.

4. Consumers should compare diesel and gasoline carefully. Today's new vehicle window sticker does not give consumers enough information to evaluate the air quality, global warming, and energy security implications of investing in a diesel or gasoline car. The EPA should require better labeling to help consumers make smarter choices. But if government fails to act, consumers can do their own analysis. At a minimum, consumers should look for a vehicle certified to the federal Tier 2 Bin 5 standard, though cleaner gasoline and hybrid-electric vehicles are available today. When evaluating a diesel vehicle's impact on oil dependence, consumers should adjust the listed fuel economy downward about 20 percent before comparing it with a gasoline vehicle. For heat-trapping gas emissions, a diesel vehicle's fuel economy should be adjusted downward about 15 percent.

Chapter 1

Why the Competition?

As of 2002, the fuel economy of the average new passenger vehicle sold in the United States stood at its lowest level in more than 20 years (Hellman and Heavenrich, 2003). This decline, combined with increases in vehicle ownership and miles traveled, has led to higher rates of oil consumption and greater emissions of heat-trapping gases. Concerns about our increasing dependence on oil and the alarming consequences of global warming have, in turn, fueled efforts to improve the fuel economy of our light-duty vehicle fleet. One option for improving fuel economy is to switch to diesel-powered vehicles.

Although Americans have steered away from diesel cars, Europeans are buying more each year, with a variety of financial incentives and regulatory benefits promoting diesel sales. Diesel cars have also emerged as a key strategy for automakers that have committed to increase their fuel economy in the European Union.

Thanks to a more efficient combustion process and the fuel's greater energy density[2], diesel engines can travel farther on a gallon of fuel than comparable gasoline engines. As a result, diesel engines generally release less carbon dioxide (CO_2)—a potent heat-trapping gas linked to global warming—from the tailpipe. The improved efficiency of diesel engines can also help reduce oil consumption. These features have led some U.S. policy makers and car manufacturers to promote light-duty diesel vehicles as a strategy for improving fuel economy, reducing our dependence on oil, and cutting global warming pollution.

Diesel also offers some performance advantages, such as good low-end towing power, that some consumers may want or need. But gasoline cars and light trucks also offer certain advantages, such as higher peak horsepower and top vehicle speeds, and cost at least a thousand dollars less than diesel vehicles. Today's diesel cars are just one of many strategies available to increase fuel economy. A variety of technologies—more efficient engines, better transmissions, improved aerodynamics, and high-strength materials—can give today's diesel a run for its money.

It should be noted that the fuel economy advantage of diesel does not translate into equivalent reductions in oil usage and heat-trapping gas emissions. Differences in the production, energy content, and formulation of low-sulfur diesel fuel and federally reformulated gasoline come into play. Relative to conventional gasoline vehicles, the energy security and global warming benefits from diesel are lower than gains in fuel economy, even accounting for diesel's higher energy density.

Furthermore, today's diesel cars release more toxic soot and smog-forming nitrogen oxides from the tailpipe than the average gasoline car. New U.S. emissions regulations (called "Tier 2") coming into full effect in 2009 will require diesel engines to pollute less. Diesel engine manufacturers are making progress in meeting this challenge, but they still face significant hurdles. While some conventional and hybrid-electric gasoline cars already meet the new standards, no diesel vehicle

2 A fuel's energy density is the amount of energy contained in a volume of fuel. Diesel contains about 13.5 percent more energy in a gallon than gasoline.

has yet passed the emissions tests for the fully implemented Tier 2 regulations.

The future of diesel for passenger cars and trucks thus remains uncertain, particularly since cleaner advanced-technology and hybrid-electric gasoline vehicles can already deliver significant progress on air quality, while reducing oil dependence and heat-trapping gas emissions. Should Americans invest in diesel or gasoline cars to save money at the pump, slow global warming, and reduce toxic pollution?

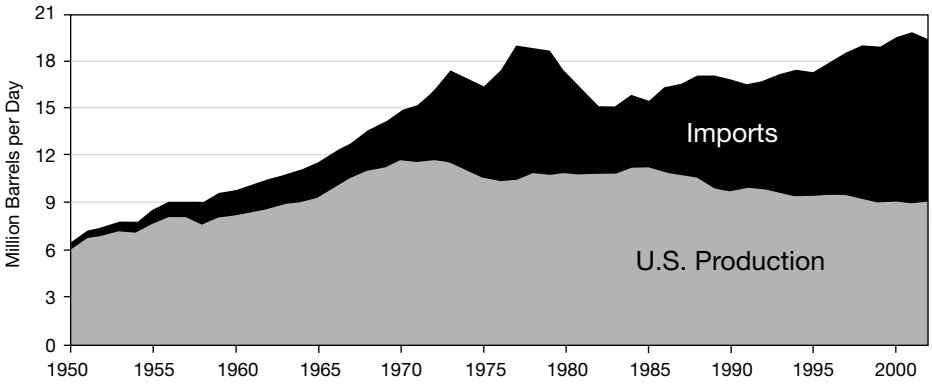
OIL USE AND GLOBAL WARMING

Over the last 40 years, U.S. reliance on imported oil has steadily increased, from nearly zero in 1950 to more than 50 percent in 2002 (Figure 1; EIA, 2003a). About one-quarter of the imported oil comes from the Persian Gulf (EIA, 2003c). The U.S. Energy Information Administration (EIA) conservatively anticipates that oil use will continue to climb through 2025, increasing by about 40 percent over the next 20 years (Figure 2; EIA, 2003b), while imports will rise to more than 60 percent. Transportation is the main culprit behind our nation's oil-thirsty habits, responsible for three-quarters of all the oil we consume.

Transportation is also a primary source of U.S. heat-trapping gas emissions, releasing more than one-third of the nation's carbon dioxide emissions in 2003 (EIA, 2003a). Light-duty cars and trucks are responsible for more than half of the transportation sector's emissions of heat-trapping gases, and their emissions are continuing to grow. If current trends continue, heat-trapping gas emissions from our nation's fleet of light-duty vehicles will total more than 2.5 billion tons of carbon dioxide-equivalent gases by 2025—a 67 percent increase from 2000 (Figure 3).[3]

Raising the fuel economy of new light-duty vehicles can slow or even reverse the trend toward increased oil consumption and heat-trapping gas emissions.[4] European countries have already committed themselves to reducing heat-trapping

Figure 1 **U.S. Oil Supply**



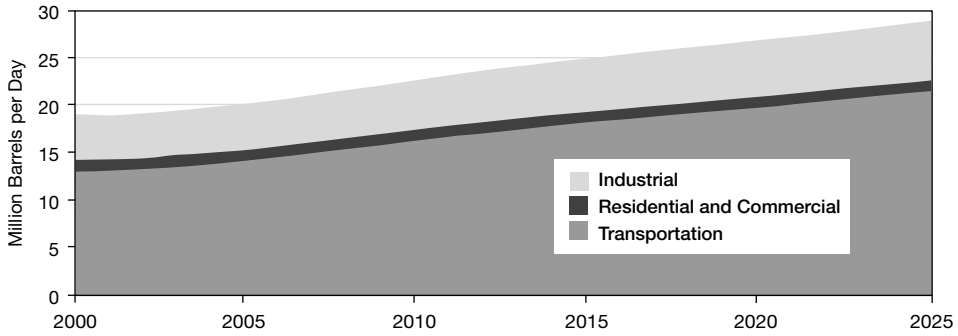
SOURCE: EIA, 2003a.

NOTE: Oil supply data include petroleum products such as motor gasoline (including blended ethanol and ethers), distillate fuel (kerosene, diesel, and other distillate), jet fuel, aviation gasoline, liquefied petroleum gas, petrochemical feedstocks, lubricants, waxes, natural gas plant liquids, and other petroleum-based products.

3 UCS calculation based on oil use projections for light-duty vehicles from EIA, 2003b, and per-gallon emission rates from Wang, 2003.

4 Increasing fuel economy is one of several measures that can help achieve these goals. Other measures include switching to lower-carbon fuels or renewable fuels, using air conditioner refrigerants with lower global warming potential, reducing the amount we drive, switching to alternative modes of transportation, and improving driving habits and vehicle maintenance.

Figure 2 **Projected U.S. Oil Usage**



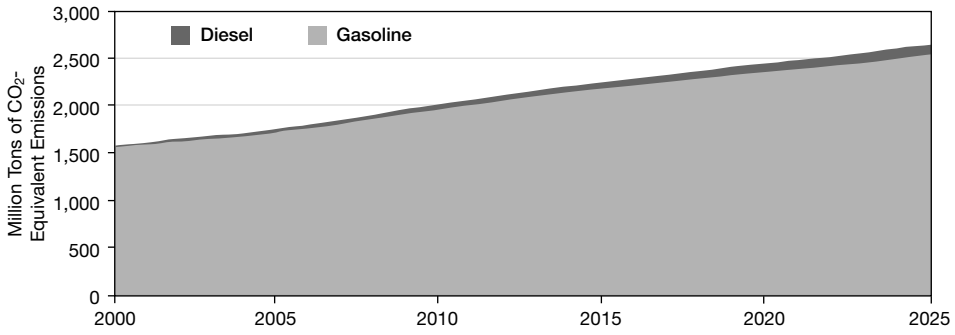
SOURCE: EIA, 2003b.

NOTES:

a. The projection for transportation demand is conservative, since the EIA assumes fuel economy for new vehicles will increase several miles per gallon compared with today's fleet, despite a 15-year trend of decreases. The fuel economy of the average new light-duty vehicle has steadily dropped from 25.9 mpg in 1987 to 23.9 mpg in 2002 (Hellman and Heavenrich, 2003). The EIA assumes new vehicle fuel economy will increase to 25.6 mpg by 2020 and 26.1 mpg by 2025. The EIA also projects light-duty vehicle miles traveled will grow by 2.4 percent per year through 2020 in its 2003 Annual Energy Outlook (compared with 2.2 percent per year in the 2002 version), and by 2.3 percent per year through 2025.

b. Oil use data include petroleum products such as motor gasoline (including blended ethanol and ethers), distillate fuel (kerosene, diesel, and other distillate), jet fuel, aviation gasoline, liquefied petroleum gas, petrochemical feedstocks, lubricants, waxes, natural gas plant liquids, and other petroleum-based products.

Figure 3 **Projected Heat-Trapping Gas Emissions from U.S. Cars and Light Trucks**



SOURCE: UCS calculation based on oil use projections for light-duty vehicles from EIA, 2003b; per-gallon gasoline and diesel heat-trapping gas emission rates from Wang, 2003.

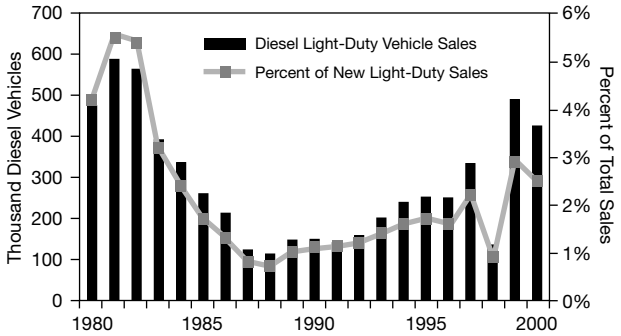
NOTE: The projection for heat-trapping gas emissions from light-duty vehicles is conservative, since the EIA assumes fuel economy for new vehicles will increase several miles per gallon higher than today's fleet, despite a 15-year trend of decreases. The fuel economy of the average new light-duty vehicle has steadily dropped from 25.9 mpg in 1987 to 23.9 mpg in 2002 (Hellman and Heavenrich, 2003). The EIA assumes new vehicle fuel economy will increase to 25.6 mpg by 2020 and 26.1 mpg by 2025.

gases from light-duty cars and trucks, and have negotiated a commitment with automakers to reduce these emissions from new vehicles by 25 percent between 1995 and 2008-2009. The higher fuel economy of diesel cars is a key element in meeting these targets (Schipper et al., 2003).

THE DIESEL DIVIDE: EUROPE AND THE UNITED STATES

Diesel passenger vehicles accounted for less than three percent of all new automobile and truck sales in the United States in 2001 (Davis and Diegel, 2002). American drivers have veered

Figure 4 **Diesel Car and Light Truck Sales, 1980–2000**



SOURCE: Davis and Diegel, 2002.

NOTE: Light trucks include passenger vehicles with a gross vehicle weight of 10,000 pounds or less.

away from diesel since the early 1980s, when a number of unreliable, noisy, and polluting diesel cars were marketed (Figure 4). Today's diesel cars have mostly overcome past performance problems, but Americans continue to buy gasoline vehicles.

Car manufacturers that see the U.S. market for diesels as untapped point to Europe as a model. About 40 percent of the European new car market is diesel-powered (Madslien, 2002), amounting to more than five million vehicles sold each year. Diesel's appeal to Europeans has been fueled by economic incentives such as substantial tax and regulatory benefits, which give it a cost advantage over gasoline. According to some researchers,

Table 1 **Diesel in the United States and Europe**

	United States	Europe	Key Differences
Diesel light vehicle market share	Less than 3%	40%	Europeans are 14 times more likely to buy diesel cars
Cost of gasoline per gallon	$1.50	$3.70 to $4.60	France and Germany pay about $1 more for gasoline than diesel; only in the United Kingdom are prices comparable
Cost of diesel per gallon	$1.45	$2.70 to $4.40	
Maximum allowable NOx for diesel vehicles (grams per mile)	0.6 to 0.9 in 2004 0.2 in 2009 (average of 0.07)	0.8 to 1.04 in 2004 0.25 to 0.5 in 2006	Europe's new standards allow three to seven times more NOx per average vehicle
Maximum allowable particulate matter (PM) for diesel vehicles (grams per mile)	0.08 to 0.12 in 2004 0.02 in 2009 (average of 0.01)	0.08 to 0.11 in 2004 0.04 to 0.06 in 2006	Europe's new emissions standards allow four to six times more particulate matter per average vehicle
Diesel sulfur content (parts per million)	500 today 15 in 2007	350 today 50 in 2005	Europe's fuel standards allow more than three times the sulfur of U.S. diesel

SOURCES: European and U.S. emissions standards and diesel content from Dieselnet, 2003; fuel prices from EIA in Davis, 2002; light-duty vehicle market share in the United States from Davis, 2002, and in Europe from Madslien, 2002.

NOTES: It is difficult to compare U.S. and European emissions standards and vehicles because test cycles, protocols, and weight classes vary significantly. The following is a summary of key differences:

a. In general, European test cycles and protocols are weaker than in the United States. The new European standards ("Euro 4") cover only the first 60,000 miles of a vehicle's life, while the new U.S. standards ("Tier 2") cover 120,000 miles. In addition, the U.S. test cycle represents a more aggressive and realistic driving style than the European test cycle.

b. The U.S. standards in this table extend to heavier weight classifications than the European standards. The Euro 4 standards distinguish between passenger vehicles and three light truck weight classes (N1-N3). The lower range of the maximum allowable emissions for the European data in this table applies to passenger cars and trucks under 2,877 pounds. The upper range includes trucks in weight class N2, which weigh up to 3,880 pounds. The U.S. Tier 2 standards, when fully implemented in 2009, apply the same emissions standards for passenger cars and light trucks, which are broken into five weight classes (T-1 through T-4 and a new class, MDPV). The U.S. data in this table for today's maximum allowable emissions extend to weight class T-3 (up to 5,750 pounds adjusted loaded vehicle weight); the data for maximum allowable emissions in 2009 include weight class T-4 and MDPV (up to 10,000 pounds gross vehicle weight rating).

c. The U.S. Tier 2 emissions standards will be phased in from 2004 through 2008, with full implementation in 2009. The Euro 4 standards will be phased in from 2005 to 2006.

d. Under the U.S. Tier 2 emissions standards, gasoline and diesel vehicles are held to the same standards. When fully implemented, average NOx emissions for gasoline and diesel passenger vehicles must equal 0.07 grams per mile, one-seventh the maximum diesel standard in Europe (Euro 4).

these economic advantages help explain why certain European countries have shown a preference for diesel cars (Mayers and Proost, 2000; Shipper et al., 2003). While diesel fuel costs about the same as gasoline in the United States, Europeans pay an average of one dollar less per gallon for diesel (Table 1). Some tax policies have also reduced the cost of purchasing and operating diesel vehicles. Lastly, the European Union's pollution standards for diesel are weaker than U.S. standards, reducing the pollution control costs for diesel cars while sacrificing public health.

Recent actions by the European Union, however, point to a shift in diesel policies. Starting in 2004, European countries can set different prices for commercial and residential diesel fuel, which will allow countries to reduce the gap in tax levels between diesel and gasoline used in cars. The European Union notes that "there are no environmental or other reasons to justify the present lower minimum rate on diesel in these circumstances" (E.U., 2003). In addition, France and Germany are leading a call for stricter regulatory standards for diesel as well as new fuel-neutral standards (UBA, 2003).

PERFORMANCE AND COST

Hauling power

Nearly all heavy vehicles and equipment (including big rigs, urban buses, tractors, and bulldozers) are powered by diesel. That's because diesel compression-ignition engines provide the muscle for applications requiring hauling power, and durability. Compared with standard spark-ignited engines, diesel compression-ignition engines operate at higher average pressures, allowing them to generate more low-end torque for hauling heavy loads. Thus, diesel engines are also advantageous in larger pickup trucks and sport utility vehicles (SUVs) used for hauling very heavy loads. However, gasoline vehicles do offer some performance advantages over diesel. Gasoline engines have superior peak horsepower, for example, with higher top vehicle speeds and better acceleration times from 30 to 60 miles per hour.

Fuel economy

Diesel cars offer higher fuel economy (when measured in miles per gallon of the appropriate fuel) than their gasoline counterparts for three reasons:

- Compression-ignition diesel engines provide high compression ratios, resulting in greater thermal efficiency than conventional gasoline engines.
- Diesel engines eliminate the throttle or butterfly valve used to control airflow and engine power output; instead, they control power by varying fuel flow. The result is reduced pumping losses, especially at low power.
- A gallon of low-sulfur diesel fuel has a higher energy density than gasoline.

Cost

Gasoline vehicles also cost less than diesel. Because diesel engines are built heavier in order to withstand higher compression ratios, they have higher materials costs than gasoline engines. So, although diesel extends the engine's life, it pushes the vehicle's price up substantially. The need for turbochargers and intercoolers, along with the use of high-pressure injectors, increases the price of diesel vehicles further still. Today's diesel cars cost between one and nearly six thousand dollars more than their gasoline counterparts (Kliesch and Langer, 2003), although the highest end of the cost differential is likely due to performance differences.

TALLYING THE BASELINE TOTALS

Thanks to their improved fuel economy relative to conventional gasoline vehicles, light-duty diesel vehicles can cut oil use and heat-trapping gas emissions from light-duty vehicles. The fuel economy improvement afforded by diesel, however, is larger than the accompanying reductions in oil use and heat-trapping gas emissions, due to differences in fuel formulation.

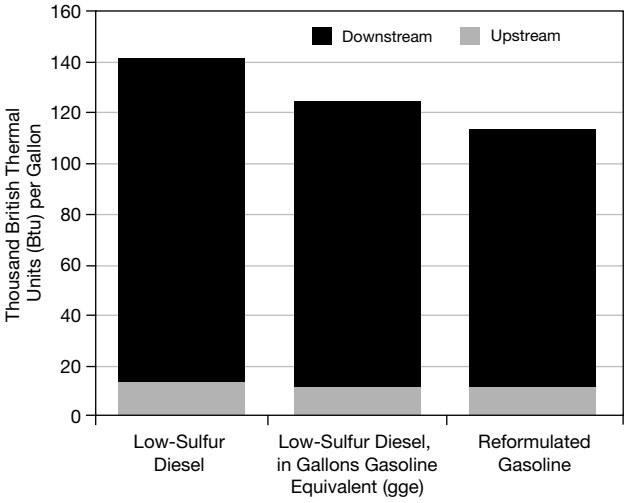
Specifically, because each gallon of low-sulfur diesel contains 13.5 percent more energy than a gallon of reformulated gasoline, its higher fuel economy is partly due to its higher energy density, not an inherent gain in efficiency. This report addresses the difference in energy densities by expressing results in gallons of gasoline equivalent (gge).

When both fuel production ("upstream" sources) and vehicle fuel use ("downstream" sources) are taken into account, a gallon of low-sulfur diesel fuel requires more oil than a gallon of reformulated gasoline (Wang, 2003). Low-sulfur diesel requires 25 percent more oil per gallon than reformulated gasoline, and 10 percent more oil per gallon of gasoline equivalent (Figure 5). About ten percent of reformulated gasoline is made up of non-petroleum constituents, such as oxygenates and additives, while low-sulfur diesel is a more pure petroleum product.

In general, the higher the fuel economy, the lower the heat-trapping gas emissions for a specific fuel. But there are three additional factors influencing the amount of heat-trapping gases released by cars and trucks:

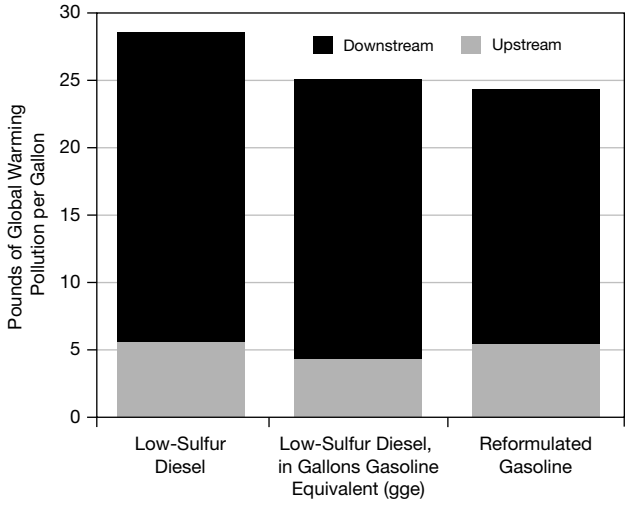
- The production and refining of each gallon of fuel results in upstream heat-trapping gas emissions. Since reformulated gasoline is a more refined product than low-sulfur diesel, its upstream emissions are slightly higher (Figure 6).
- The carbon content of the fuel directly affects the amount of carbon dioxide released from the tailpipe. Diesel fuel contains more carbon than gasoline, so its tailpipe carbon dioxide emissions are higher.
- Other heat-trapping gases are released during vehicle operation (such as refrigerants in the air conditioning system and black carbon soot released from the tailpipe). There is no consensus on how to account for all the heat-trapping

Figure 5 **Oil Usage per Gallon**



SOURCE: UCS calculation from Wang, 2003.

Figure 6 **Global Warming Pollution per Gallon**



SOURCE: UCS calculation from Wang, 2003.

gases emitted as a result of vehicle operation, but some studies indicate that these pollutants, particularly carbon soot, could be an important factor in global warming (see box, "Does diesel soot contribute to global warming?").

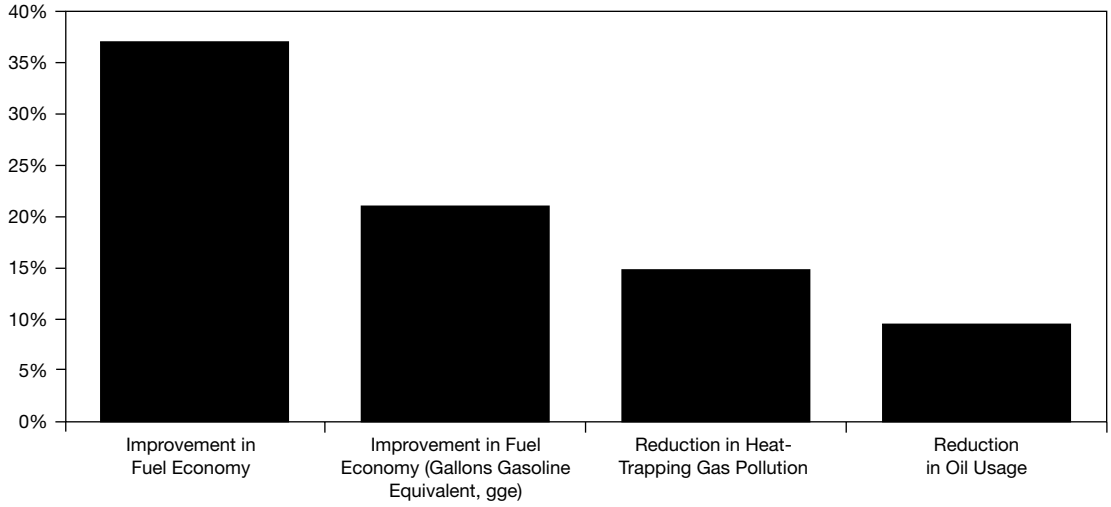
Taking both upstream and downstream emissions into account, each gallon of gasoline combusted results in about 24 pounds of heat-trapping gases, while a gallon of diesel fuel results in 28 pounds of heat-trapping gases—a 17 percent increase. On an energy-equivalent basis, each gallon of diesel fuel results in about three percent more heat-trapping gas emissions than gasoline.

Let's say a conventional diesel car achieves a 37 percent improvement in fuel economy relative to a gasoline car. Adjusting for the difference in energy density, the fuel economy advantage of the diesel vehicle would be reduced to 21 percent (Figure 7). The diesel car would release 15 percent less heat-trapping gas emissions over its lifetime than its gasoline counterpart.[5] And, since diesel

Does diesel soot contribute to global warming?

Early studies indicate that the black carbon soot emitted by diesel vehicles may be a potent heat-trapping gas, potentially undermining some of diesel's heat-trapping gas emissions advantage over gasoline (Jacobson, 2001 and 2002). These studies, which were based on emissions standards that expired in 2003, have found that a conventional diesel car may release more heat-trapping gases than the average gasoline car due to the increased carbon soot produced by diesel combustion. With the implementation of new "Tier 2" standards, diesel vehicle manufacturers will be required to cut particulate emissions significantly, but the Environmental Protection Agency (EPA) anticipates that an increase in the number of diesel cars will lead to increased particulate emissions regardless of the new standards.

Figure 7 **Benefits of Diesel (Compared with Gasoline)**



SOURCE: UCS calculations and emission data from Wang, 2003. Assumes no rebound effect from the higher fuel economy and fuel cost savings.

5 In this example, we assume both cars travel 172,902 miles in their lifetimes, though the higher fuel economy of the diesel vehicle may result in more miles traveled each year.

contains more petroleum than gasoline, oil use would drop about nine percent. Thus, though there is a link between fuel economy, heat-trapping gas emissions, and oil use, some of diesel's advantages are reduced due to its higher carbon and petroleum content.

TAILPIPE POLLUTION

Compared with current gasoline vehicles equipped with three-way catalysts, today's diesel engines release much higher levels of soot (particulate matter, or PM) and smog-forming nitrogen oxides (NOx; see Chapter Three for a discussion of the impact vehicle pollution has on public health). The soot from diesel vehicles has been associated with a wide range of health problems, including asthma, cancer, and even premature death. Nitrogen oxides react with sunlight to produce smog, which can cause respiratory problems and has also been linked with premature death.

U.S. tailpipe standards for diesel cars have historically been weaker than those for gasoline cars, allowing diesel cars to emit more toxic soot and nitrogen oxides. For the first time, the new Tier 2 tailpipe standards coming into full effect in 2009 will hold diesel vehicles to the same tiered structure of standards as gasoline vehicles. As we discuss in Chapter Four, however, the tiered structure gives automakers the flexibility to produce some cars that release two times more soot and smog-forming pollution than the average new vehicle and still meet their targets. A key to meeting the Tier 2 standards will be the availability of low-sulfur diesel fuel, which is required by federal law starting in mid-2006. Federally reformulated low-sulfur gasoline is also required under Tier 2.

Pollution controls for diesel engines needed to meet the Tier 2 standards are in varying states of development (see Appendix A for a description of diesel cleanup options). There is reason to be optimistic that manufacturers will meet the weaker categories of Tier 2, but the resulting pollution controls will likely exact a fuel economy penalty, reducing some of diesel's advantage over gasoline. In addition, whether diesel cars will be able to match the emissions performance of some of today's cleaner gasoline engines is unclear.

For this analysis, we optimistically assume that evolving diesel emission controls will be able to meet the average Tier 2 emissions (Bin 5).[6] There is some speculation, though, that diesel vehicles—particularly light trucks—will only be able to meet the weakest of the Tier 2 standards (Bin 8). Vehicles that certify to this weakest tier can release twice as much particulate matter and nearly three times as much nitrogen oxides as the average new car.

THE ROAD AHEAD

New technologies under development for both gasoline and diesel cars can boost fuel economy, cut emissions of heat-trapping gases, and reduce our dependence on oil. By tapping into the expertise of automotive engineers in Detroit and around the world, conventional cars can be replaced with safer, more fuel-efficient models that provide American consumers with a wider array of vehicle choices and save them money at the pump. This analysis puts gasoline and diesel engines to the test to see which vehicles give American consumers the best buy for their money.

6 Under the Tier 2 standards, average nitrogen oxide emissions must equal the Bin 5 standard, which requires vehicles to certify at 0.07 grams/mile (g/m) of nitrogen oxides, 0.09 g/m non-methane organic gases (NMOG), and 0.01 g/m of particulate matter. Bin 8, the weakest of the Tier 2 standards, allows tailpipe emissions of 0.2 g/m of nitrogen oxides, 0.125 g/m of non-methane organic gases, and 0.02 g/m of particulate matter.

Chapter 2

Comparing Apples: Diesel vs. Gasoline

While diesel engines have an efficiency advantage over gasoline engines and offer some improved performance characteristics, they also have inherently higher costs, use higher-energy fuel, and face unique emissions challenges. This makes a simple apples-to-apples comparison of fuel economy difficult. Furthermore, engine technologies are not the only way to improve fuel economy. Improved transmissions, advanced materials, better aerodynamics, rolling resistance improvements, and even hybridization can also improve fuel economy for both gasoline and diesel vehicles, often at a lower cost per gallon saved.

To help evaluate and compare the energy security and environmental performance of diesel and gasoline vehicles, this study examines the costs and fuel economy impact of applying different technology packages to both diesel and gasoline vehicles. These packages are similar to those used in previous studies of gasoline vehicles (DeCicco et al., 2001; Friedman et al., 2001; Friedman 2003), and each has been applied to the five major vehicle classes: compact cars, "family" cars, minivans, full-size pickups, and mid-size SUVs.

To ensure the best possible apples-to-apples comparison, we applied a vehicle energy use simulation model to predict likely fuel economy increases for vehicles with *equivalent* 0 to 60 mph acceleration performance. However, because diesel engines provide more torque at low speeds than gasoline vehicles and less torque at high speeds, the diesel vehicles in this study have better performance around town (acceleration from 0 to 30 mph), but worse performance on the highway (acceleration from 30 to 60 mph). A perfect apples-to-apples comparison with gasoline vehicles is therefore not possible, but this was chosen as the best compromise since some consumers may place more value on either city or highway driving. Economic, fuel savings, and related calculations based on these results take into account a 10 percent "rebound" effect (the possibility that consumers may drive more if the cost of driving is decreased).

This chapter summarizes our findings for a fleet of diesel cars and trucks and compares them with previous findings for a fleet of gasoline vehicles. The results indicate how diesel and gasoline vehicles would compete using some technologies that could be implemented today and others that could be implemented within the next 10 to 15 years. For detailed results on each technology package applied to the five major car and truck classes, see Appendix B. All costs are presented in year 2000 dollars and assume that each vehicle being evaluated will be in mass production (i.e., each of the "Big Six" automakers produces at least 200,000 units of that model per year).

TECHNOLOGY PACKAGES

Five technology packages have been evaluated to establish the fuel economy potential for diesel and gasoline vehicles. Three use conventional technologies (baseline, moderate, and advanced) and two raise fuel economy even higher by incorporating hybrid-electric technologies (advanced mild hybrid and advanced full hybrid). Excluding the issue of diesel emission controls, the baseline and moderate packages could be widely implemented

across the U.S. passenger fleet today if automakers had included these existing technologies in past market plans. Despite the fact that this has not happened, these packages could still be widely implemented within the next five to seven years, although for diesel vehicles this will depend on whether automakers are successful in developing the necessary emission control technologies. The advanced and hybrid packages could be widely implemented within the next 10 to 15 years, again with the same caution on emission controls for diesel vehicles.

Each of the improved technology packages is designed to meet Tier 2 Bin 5 emission levels and includes some combination of efficient engine, improved transmission, vehicle load reduction, idle-off technology, and/or hybridization. With the exception of the emission control technology and diesel engines, these packages are identical to those used in a previous study of conventional gasoline and gasoline hybrid-electric vehicle technology (Friedman, 2003), and that report should be consulted for details not included here.

The fuel economy and performance of the baseline, moderate, and advanced diesel packages were evaluated using the vehicle system simulation tool known as the Modal Energy and Emissions Model (MEEM), a comprehensive vehicle model (NCHRP, 2001) that has been used in several earlier reports (DeCicco et al., 2001; An et al., 2002; Friedman, 2003). The fuel economy of the two diesel hybrid packages was estimated, not simulated, assuming the same relative improvement in fuel economy previously observed for advanced gasoline mild and full hybrids compared with conventional advanced gasoline vehicles (Friedman, 2003).[7] Because some of diesel's efficiency advantages overlap those provided by hybrids, these results are likely to overestimate the potential efficiency gains from diesel hybridization, but are presented here as an optimistic case.[8]

The modeled fuel economy of each diesel package has been reduced by five percent to account for the fuel economy penalty associated with achieving Tier 2 Bin 5 emission levels. This penalty is an estimate based on a combination of fuel penalties associated with nitrogen oxide control, which engine manufacturers estimate lowers fuel economy by four to five percent (Plotkin et al., 2002), as well as the fuel loss resulting from any active regeneration needed to clean out particulate matter traps.[9]

Additional details on each technology package are presented in Appendix B.

MEASURING UP

The costs and benefits of the diesel and gasoline packages presented in this study must be compared with today's average passenger vehicle. The bar set by the average model year (MY) 2000 vehicle is quite low: a federal Corporate Average Fuel Economy (CAFE) rating of only about 24 miles per gallon of gasoline equivalent (mpgge). Table 2 shows that this vehicle will get closer to 20 mpgge when driving in real-world conditions and will have a manufacturer's suggested retail price (MSRP) of about $20,700 when incorporating the emission control technology required to meet Tier 2 Bin 5 standards. In other words, this vehicle's owner will spend the equivalent of more

7 The advanced mild hybrid diesel package is assumed to achieve an average fuel economy improvement of 19 percent relative to the conventional advanced diesel package, while the advanced full hybrid diesel package is assumed to achieve an average fuel economy improvement of 41 percent relative to the conventional advanced diesel package. The improvement for the advanced full hybrid is similar to that seen in Weiss et al., 2003 for their hybrid case.

8 Specifically, hybrids help reduce engine operation at low power (where gasoline engines are typically very inefficient). Diesel engines, however, are not as inefficient at low power levels, so some of this advantage is lost. Other advantages of hybridization, such as regenerative braking and idle-off operation, will still apply.

9 The penalty for nitrogen oxide control currently ranges from two to six percent for heavy-duty vehicles (Johnston, 2003).

Table 2 **Lifetime Impact of Model Year (MY) 2000 Light-Duty Vehicles**

	Average Passenger Vehicle
CAFE-rated fuel economy[a] (mpg)	24.4
Gasoline-equivalent CAFE fuel economy[b] (mpgge)	24.4
Real-world fuel economy[c] (mpgge)	20
MSRP[d]	$20,697
Lifetime fuel cost[e]	$9,145
Lifetime global warming pollution[f] (tons)	103
Lifetime oil requirement[g] (barrels)	206

NOTES:

a. Modeled composite city/highway fuel economy over the EPA test cycle used in determining Corporate Average Fuel Economy (CAFE) compliance. Heavenrich and Hellman, 2003 indicate the actual value was 24.3 mpg.

b. CAFE test results adjusted for the energy content in the fuel relative to gasoline.

c. Gasoline-equivalent CAFE results adjusted by 18% to better represent on-road performance.

d. Manufacturer's suggested retail price. Excludes tax, title, and destination charges. Includes costs to meet Tier 2 Bin 5 standards compared with a standard MY2000 car or truck.

e. Lifetime fuel cost based on: average gasoline price of $1.40 per gallon; 15-year average vehicle lifetime; annual mileage of 15,600 in the first year, declining by 4.5% per year; and real discount rate of 5% (equivalent to an 8% new car loan).

f. Lifetime global warming pollution presented as carbon dioxide-equivalent emissions from the vehicle tailpipe and upstream fuel manufacturing and delivery. Emissions from vehicle manufacturing, refrigerant leaks, and other sources are not included. Emissions are based on the same vehicle lifetime and mileage estimates used to calculate lifetime fuel cost.

g. Lifetime oil requirement presented as the amount of oil required to make the gasoline used during the vehicle's lifetime, incorporating the same life and mileage estimates used to calculate lifetime fuel cost.

than $9,000 on gasoline over the vehicle's lifetime (at $1.40 per gallon), while emitting 103 tons of global warming pollution and consuming 206 barrels of oil.[10]

In comparison, the savings from an improved fleet of conventional gasoline or diesel vehicles, or a fleet of gasoline or diesel hybrids, are impressive (Table 3, pg. 16). Conventional technology and improved gasoline engines can increase fuel economy by 30 to 70 percent, reaching more than 40 mpg. Hybrid technology combined with advanced gasoline engines can more than double fuel economy, reaching nearly 60 mpg.

The baseline diesel engine can improve fuel economy by about 20 percent on a gasoline-equivalent basis. This may seem low compared with the oft-quoted 40 to 60 percent gain, but the high end of this range (50 to 60 percent) often results from comparing gasoline vehicles with diesel vehicles that offer worse acceleration performance (as in MY 2003 Volkswagen vehicles). The rest of the inflated fuel economy estimate results from ignoring diesel's 13 percent higher energy density[11] (i.e., using miles per gallon of diesel fuel instead of miles per gallon of gasoline equivalent) and the five percent fuel economy penalty incurred by the emission controls needed to meet tailpipe emissions standards being phased in during this decade.

In this study, baseline diesel vehicles improve fuel economy by about 44 percent when excluding these two factors and comparing vehicles with the same 0 to 60 mph acceleration times. The fuel economy penalty due to emission controls reduces the improvement to about 37 percent, and taking diesel's higher energy density into account results in a final gasoline-equivalent fuel economy improvement of 21 percent.

With this in mind, the combination of conventional vehicle technology and diesel engines available in the United States today could increase fuel economy as much as 42 percent, reaching nearly 35 mpgge. The use of more advanced technology along with advanced diesel engines under development could produce a better than 90 percent improvement in fuel economy; hybrids with advanced diesel engines could increase fuel economy as much as 170 percent, reaching 65 mpgge or better.

Comparing the fuel economy potential of similar gasoline and diesel technology packages listed in Table 3, it appears that diesel vehicles

10 Gasoline pricing is based on long-term projections (EIA, 2003). Given recent trends, these costs are probably low and can therefore be considered conservative.

11 Specifically, the energy content of 15 ppm low-sulfur diesel fuel compared with 30 ppm low-sulfur reformulated gasoline, both of which are required for passenger vehicles nationally by 2006.

Table 3 **Impact of Improved Gasoline, Diesel, Conventional, and Hybrid Technology**[a]

Vehicle Technology	Baseline	Moderate	Advanced	Advanced	Advanced
Vehicle Type	**Conventional**	**Conventional**	**Conventional**	**Mild Hybrid**	**Full Hybrid**
Gasoline					
CAFE-rated fuel economy[b] (mpg)	24.4	32.8	41.6	49.4	58.6
Gasoline-equivalent CAFE fuel economy[c] (mpgge)	24.4	32.8	41.6	49.4	58.6
Real-world fuel economy[d] (mpgge)	20	26.9	34.1	40.5	48
Fuel economy improvement from baseline		34%	70%	102%	140%
Incremental retail cost increase[e]		$591	$1,675	$3,136	$4,469
Lifetime fuel cost savings[f]		$2,154	$3,549	$4,395	$5,108
Lifetime net savings[g]		$1,563	$1,874	$1,259	$639
Lifetime global warming pollution savings[h] (tons)		24	40	50	58
Cost-effectiveness (net cost per ton of CO_2-equivalent emissions)		-64	-47	-25	-11
Lifetime oil savings[i] (barrels)		49	80	99	115
Cost-effectiveness (net cost per barrel of oil)		-32	-23	-13	-6
Diesel					
CAFE-rated fuel economy[b] (mpg)	33.6	39.5	52.9	62.9	74.6
Gasoline-equivalent CAFE fuel economy[c] (mpgge)	29.6	34.8	46.6	55.4	65.7
Real-world fuel economy[d] (mpgge)	24.3	28.5	38.2	45.5	53.9
Fuel economy improvement from baseline	21%	42%	91%	127%	169%
Incremental retail cost increase[e]	$2,032	$2,284	$3,376	$4,823	$6,156
Lifetime fuel cost savings[f]	$2,309	$3,271	$4,697	$5,377	$5,947
Lifetime net savings[g]	$276	$987	$1,321	$554	-$209
Lifetime global warming pollution savings[h] (tons)	13	26	44	54	61
Cost-effectiveness (net cost per ton of CO_2-equivalent emissions)	-22	-39	-30	-10	3
Lifetime oil savings[i] (barrels)	14	41	81	100	116
Cost-effectiveness (net cost per barrel of oil)	-19	-24	-16	-6	2

NOTES:

a. See appendices for discussion of methodology, data, and detailed results.

b. Composite city/highway fuel economy over the EPA test cycle used in determining Corporate Average Fuel Economy (CAFE) compliance.

c. CAFE test results adjusted for the energy content in the fuel relative to gasoline.

d. Gasoline-equivalent CAFE results adjusted by 18% to better represent on-road performance.

e. Increase in manufacturer's suggested retail price. Excludes tax, title, and destination charges. Includes net costs to meet Tier 2 Bin 5 standards compared with baseline vehicle that meets the same emission levels.

f. Lifetime fuel cost savings based on the difference between the baseline gasoline vehicle and the cases shown here. Includes the following assumptions: average gasoline price of $1.40 per gallon; average diesel price of $1.40 per gallon; 15-year average vehicle lifetime; annual mileage of 15,600 in the first year, declining by 4.5% per year, and modified by a 10% rebound effect based on the per-mile cost of driving; and real discount rate of 5% (equivalent to an 8% new car loan).

g. Lifetime net savings based on the difference between the increase in MSRP and the lifetime fuel cost savings.

h. Lifetime global warming pollution savings presented as carbon dioxide-equivalent emissions from the vehicle tailpipe and upstream fuel manufacturing and delivery. Emissions from vehicle manufacturing, refrigerant leaks, and other sources are not included. Emissions are based on the same vehicle lifetime and mileage estimates used to calculate lifetime fuel cost.

i. Lifetime oil requirement presented as the amount of oil required to make the gasoline or diesel fuel used during the vehicle's lifetime, incorporating the same life and mileage estimates used to calculate lifetime fuel cost.

maintain their efficiency advantage and reach higher fuel economy levels than achievable with comparable gasoline vehicles. The table also indicates, however, that the inherently high costs of diesel technology significantly drive up the incremental cost to consumers and diminish the overall cost-effectiveness of the diesel packages.

FUEL ECONOMY COMPARISON

Figure 8 summarizes the costs to consumers for the incremental fuel economy improvements derived from our various technology packages. The lower line represents costs for gasoline technology, while the upper line represents costs for diesel technology.

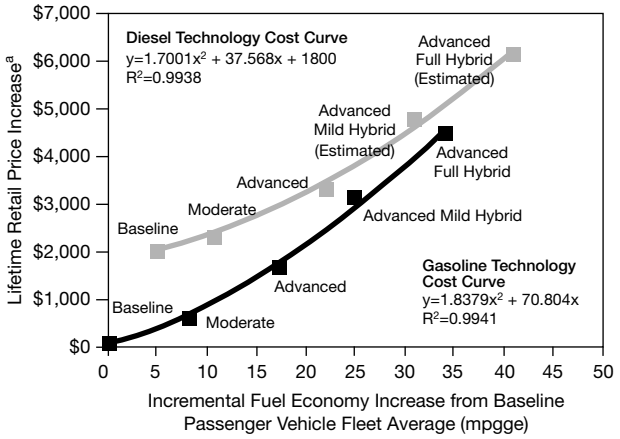
As noted above, this figure illustrates how diesel vehicles using the same technology packages as gasoline vehicles deliver larger fuel economy gains due to their inherent efficiency advantage. For example, the advanced conventional gasoline package improves fuel economy by about 17 mpgge while the advanced conventional diesel package provides a 28.5 mpgge increase.

Figure 8 also shows that consumers will face higher costs for the same improvement in fuel economy when they choose diesel over gasoline. This finding is even more evident in Figure 9, which compares the cost of gasoline and diesel engines in reaching four specific fleetwide fuel economy levels.

Achieving a fleet average fuel economy of approximately 30 mpgge using a diesel technology package ($2,000) would cost about four times as much as reaching the same level with a gasoline technology package ($500). A 40 mpgge fleet would cost about 75 percent more with a diesel package ($2,800) instead of a gasoline package ($1,600), and so on. Overall, these results indicate that gasoline vehicles are the less expensive means for reaching fuel economy targets for the foreseeable future.

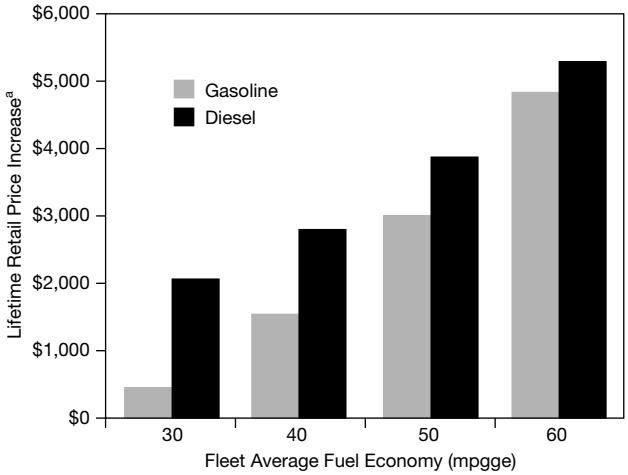
At higher fuel economy levels, the price difference between gasoline and diesel technology packages narrows, but does not disappear in the range of fuel economies investigated here. This indicates that the cost for each additional increase

Figure 8 **Fuel Economy Cost Curves for Gasoline and Diesel Vehicles**



NOTE:
a. Includes the present value of battery replacement costs for hybrids.

Figure 9 **Incremental Price Comparison for Diesel and Gasoline Vehicles**



NOTE:
a. Includes the present value of battery replacement costs for hybrid vehicles where appropriate.

in fuel economy (the marginal cost) is higher for the gasoline packages. Since gasoline engines are less efficient than diesel engines, the gasoline packages must rely on increasingly expensive technologies to keep pace.

A gasoline vehicle, for example, requires a package including both advanced conventional and mild hybrid technology to obtain a fleet average fuel economy of 50 mpgge, while a diesel vehicle needs only advanced conventional technology. The added hybrid technology required for the gasoline vehicle does not cancel out the price difference between the gasoline and diesel engines, but it does narrow the gap. In addition, as more significant aerodynamic improvements and weight reduction are implemented to achieve higher fuel economy levels, the engine can be downsized without sacrificing performance. Because smaller engines cost less, these improvements help minimize the financial impact of the more expensive diesel engine.

Even when accounting for the uncertainty in our analysis, it is clear that gasoline vehicles will remain less expensive than diesel vehicles up to a fleetwide fuel economy level of 50 to 55 mpgge. Diesel vehicles may have similar initial costs to gasoline vehicles at very high fuel economy levels, but they will not have the same potential to meet the extremely low tailpipe pollutant levels achievable with gasoline vehicles (as discussed in the next chapter).

ENERGY SECURITY AND COST-EFFECTIVENESS

Gasoline appears superior to diesel not only with respect to the initial vehicle price but also its cost-effectiveness in reducing oil dependence. Two counteracting factors influence this result:

- Diesel has a higher energy density than gasoline and requires more oil to produce, reducing the cost-effectiveness of the diesel technology packages at a given fuel economy level.[12]
- Low-sulfur diesel is expected to be less expensive than low-sulfur gasoline on a gallon of gasoline-equivalent basis, increasing the fuel cost savings achieved by the diesel technology packages at a given fuel economy level. This partially compensates for the decreased cost-effectiveness noted above, but if diesel vehicles become popular, market demand for the fuel may increase its price and reduce this advantage.[13]

Both of these factors have been taken into account in developing our apples-to-apples comparison of oil security cost-effectiveness (Figure 10). Across the spectrum of improvements that could be reasonably achieved over the next 10 to 15 years—cutting the oil dependence of new passenger vehicles as much as 50 percent—the gasoline technology packages are 40 to 50 percent more cost-effective than the diesel technology packages. As with the initial vehicle price, this gap diminishes at higher levels, but does not disappear.

12 A gallon of low-sulfur diesel fuel requires about 25 percent more oil to produce than a gallon of low-sulfur reformulated gasoline. A gallon of gasoline equivalent requires only about 10 percent more oil for diesel than gasoline. This results from the use of ethanol and other non-petroleum additives in the gasoline blending process.

13 The lower cost is the corollary to the higher oil content—oil is less expensive than the additives used in gasoline. Gasoline is assumed to cost $1.40 per gallon (EIA, 2003). Diesel is assumed to have the same cost as gasoline on a volume basis, $1.40 per gallon, which translates into $1.23 per gallon of gasoline equivalent. The EIA expects a one- to three-cent lower price for diesel on a volume basis, but with a much lower sales volume (EIA, 2003).

Figure 10 **Oil Security Cost-Effectiveness for Diesel and Gasoline Vehicles**

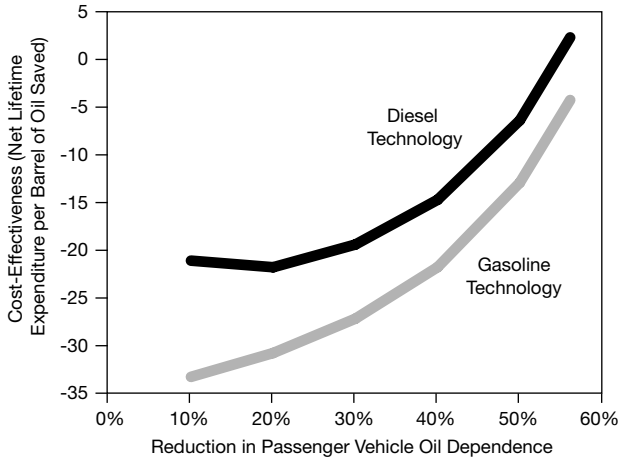
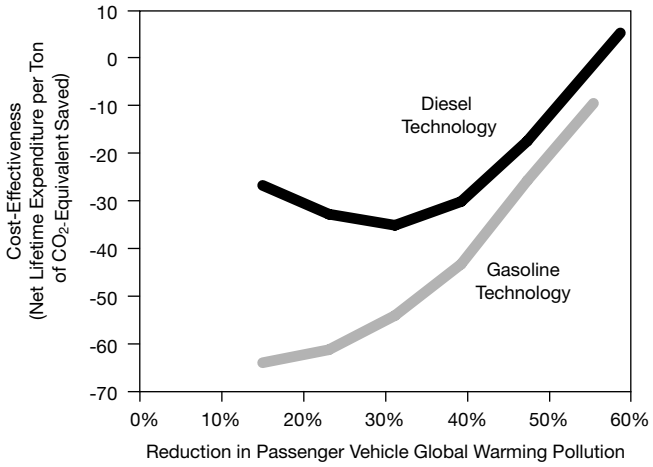


Figure 11 **Heat-Trapping Gas Cost-Effectiveness for Diesel and Gasoline Vehicles**



HEAT-TRAPPING GASES AND COST-EFFECTIVENESS

As with vehicle price and oil security, gasoline vehicles appear to be more cost-effective than diesel vehicles in cutting emissions of the heat-trapping gases that lead to global warming. The gap in this case, though, is smaller than that seen for oil use.[14]

Across the spectrum of cuts that could be reasonably made in passenger vehicle heat-trapping gases over the next 10 to 15 years without switching to alternative fuels or fuel cells (as much as a 50 percent reduction), the gasoline technology packages are 40 percent to better than 80 percent more cost-effective than diesel (Figure 11). However, the gap in cost-effectiveness between gasoline and diesel vehicles is significantly smaller above a 50 percent reduction (though it should be noted that diesel does not have the same potential to achieve extremely low tailpipe pollutant emissions, which are discussed in the next chapter).

Another interesting conclusion we can draw from Figure 11 is that diesel's cost-effectiveness starts off worse at lower levels of reduction in global warming pollution compared with some higher levels. A similar trend in reducing oil demand can be seen in Figure 10. This reduced cost-effectiveness indicates that merely installing today's diesel engine in today's average vehicle is not enough. Instead, consumers can save more in the long run by paying a small amount for additional conventional vehicle improvements up front. If automakers are already adding $2,000 to the vehicle price by installing a diesel engine and the necessary emission controls, they should optimize the vehicle's cost-effectiveness by also including a $200 to $300 package that provides improved aerodynamics, better tires and transmissions, and high-strength materials.

EXTREME TOWING PERFORMANCE

One area where diesel vehicles will likely outperform gasoline vehicles is in the more extreme towing applications for SUVs and pickups.

14 On a volume basis, a gallon of low-sulfur diesel fuel produces about 17 percent more CO2-equivalent emissions than a gallon of low-sulfur reformulated gasoline, excluding the effects of soot and nitrous oxide. But, on a gallon of gasoline-equivalent basis, diesel fuel emits only about three percent more heat-trapping gases than gasoline. This is due to the fact that the blending agents in gasoline produce heat-trapping gas emissions (even though they are not derived from petroleum).

While all of the vehicles we evaluated are quite capable of towing a ¾- to one-ton load up a steep six percent grade at 50 miles per hour, the diesel vehicles will typically have an advantage, especially in towing even heavier loads.

This diesel advantage is due to two factors:

- Diesel vehicles inherently have better torque at lower and mid-range engine speeds. To match a diesel vehicle's capability for hauling heavy loads, a gasoline vehicle would have to operate in lower gears and at higher engine speeds.
- As previously discussed, the inherent efficiency advantage of diesel engines means a diesel vehicle can achieve similar fuel economy to a gasoline vehicle using less technology, and will therefore tend to incorporate less engine downsizing. For example: while an advanced mild hybrid gasoline pickup and an advanced conventional diesel pickup can achieve similar fuel economy and performance under standard operating conditions, the diesel vehicle will have a larger engine and superior towing capacity. The diesel pickup will cost more than its gasoline counterpart, but those in the market for extreme towing capability may be willing to pay that premium.

Chapter 3

Pollution, Public Health, and Tailpipe Standards

Both diesel and gasoline vehicles pollute, but the public health threat from diesel has historically loomed larger. Per mile traveled, today's conventional diesel engines release more toxic air contaminants, soot, and smog-forming emissions than their gasoline counterparts. These pollutants can cause or exacerbate a wide variety of ailments (such as asthma, other respiratory diseases, cancer) and may even result in premature death.

While improperly maintained gasoline cars, known as "high emitters" or "smoking vehicles," can rival or even exceed diesel's pollution levels (see box, below), the average diesel car releases ten to several hundred times more soot and about twice as much smog-forming pollution as a properly maintained gasoline car. Tomorrow's diesel cars and trucks will be much cleaner than the current generation, but doubts remain about whether diesel engines will ever be able to match the cleanest gasoline engines.

SMOG-FORMING POLLUTANTS

Cars and trucks release smog-forming nitrogen oxides and hydrocarbons from their tailpipes. In the presence of sunlight, these compounds can react to form urban ozone, or smog. Nitrogen oxides carry a double-edged threat: in addition to smog formation, they are also responsible for the secondary formation of particles in the atmosphere.

Approximately 37 percent of the nation's population currently lives in areas that exceed the federal ozone standard (EPA, 2003). Between 1970 and 1993, air quality for ozone had been steadily improving, but progress stalled during the past decade, with national ozone levels remaining

Why tailpipe standards are not enough

Routine deterioration with age, tampering with emission controls, improper maintenance, and poor engineering all lead to more tailpipe pollution. "High-emitting" vehicles, in fact, can release up to 50 times more pollution than new car standards dictate (Wenzel and Ross, 1996; Ross et al., 1998), and this is no small problem. A study of in-use emissions in Denver found that 30 percent of gasoline vehicles on the road were high emitters (Norbeck, 1998).[15]

There may be even more reason to be concerned about diesel vehicles. Studies suggest the average diesel engine has a particulate emission profile that closely matches or even exceeds that of a high-emitting gasoline vehicle (Knapp et al., 2001; Norbeck et al., 1998; Cadle et al., 1997). Like today's gasoline cars and trucks, diesel vehicles may release higher emissions in the real world than certification values indicate, particularly the first few generations that new pollution controls are used.

15 The study evaluated in-use emissions from 129 gasoline cars. High emitters were defined as Tier 1 vehicles releasing at least 1.5 times more hydrocarbons, nitrogen oxides, or carbon monoxide than allowed by engine certification emission levels. For Tier 0 vehicles, high emitters released two times more hydrocarbons or carbon monoxide, or four times more nitrogen oxides than allowed.

fairly constant. The U.S. government speculates that nitrogen oxide emissions may be largely to blame (EPA, 2003).[16] While hydrocarbon emissions[17] have decreased 40 percent during the past 20 years, nitrogen oxide emissions have only fallen 15 percent.

Smog can irritate the respiratory system, reduce lung function, exacerbate asthma, damage the lining of the lungs, and aggravate chronic lung diseases (EPA, 2002). On smoggy days, hospital admissions, especially for asthma, escalate (Koren, 1995; White, 1994), and even at levels below the current federal standard, smog can lead to higher death rates (ATS, 1996).

Children may be particularly sensitive to the harmful effects of air pollution. Because they breathe at faster rates than adults, children and their developing lungs experience greater exposure to air pollutants. Numerous studies have already found that air pollution exacerbates asthma, but a new study of Southern California found that air pollution may actually cause asthma in otherwise healthy children (McConnell et al., 2002). In communities with the highest ozone levels, children who participated in sports were more than three times as likely to become asthmatic compared with less active children.

Another study found that asthmatic children experienced significant problems breathing even at ozone levels below the EPA's National Ambient Air Quality Standards (NAAQS) (Gent et al., 2003).[18] This study concluded that air quality standards are not sufficient to protect these more vulnerable members of the population.

Today's cars

Light-duty cars and trucks are responsible for about one-fifth of the nation's smog-forming pollutants (nitrogen oxides and hydrocarbons combined).[19] If diesel vehicles comprised a larger share of the fleet, these emissions would likely be higher, since current diesel cars are allowed to release 40 percent more smog-forming pollutants than gasoline cars.[20]

Tomorrow's cars

Properly functioning catalytic converters have cut the smog-forming emissions of gasoline cars, which should be able to meet even the cleaner categories (called "Bins") under the Tier 2 standards without major problems (see EEA, 1997 for a description of the gasoline emission controls needed to meet Tier 2). The key for gasoline cars and trucks is that their pollution controls must remain in good working condition throughout the lifetime of the vehicle.

Diesel cars and trucks face much larger obstacles, since emission controls for nitrogen oxides under diesel's lean combustion environment are still in the development phase (see Appendix A for

16 In certain areas of the country, such as Los Angeles and San Francisco, monitoring data indicate that ozone levels are higher on the weekend than weekdays. This result is counterintuitive, since traffic is often reduced on the weekend and there is less industrial activity. Some researchers have postulated that it is more critical to reduce hydrocarbons in areas such as the Los Angeles basin, and that further reductions in nitrogen oxides may not reduce ozone levels. However, the California Air Resources Board (CARB, 2003b) recently issued a report identifying other possible causes for the weekend ozone effect, and found no compelling evidence to derail strategies for reducing nitrogen oxides. For a summary of these reports, see *www.arb.ca.gov/aqd/weekendeffect/weekendeffect.htm*.

17 In the form of volatile organic compounds (VOCs).

18 Asthmatic children experienced a 35 percent increase in wheezing and a 47 percent increase in chest tightening when ozone levels increased 50 parts per billion (ppb) but remained below the EPA standards.

19 UCS analysis based on EPA emission trends data for 2001 (EPA, 2003b).

20 Diesel cars can release 1.6 g/m of non-methane hydrocarbons (NMHC) and nitrogen oxides, while gasoline cars are held to 0.9 g/m. In general, diesel cars release more nitrogen oxides than gasoline cars, while gasoline cars release more hydrocarbons. However, while both diesel and gasoline cars are held to an NMHC standard of 0.31 g/m, a diesel car can release two times more nitrogen oxides (1.25 g/m versus the gasoline standard of 0.6 g/m). In general, diesel cars release less NMHC than the standard allows, while gasoline cars release less nitrogen oxide.

details). Recent experience offers cause for concern.

In the 1990s, diesel engine manufacturers responsible for the majority of heavy-duty engine sales allegedly used "defeat devices" to bypass air pollution regulations for nitrogen oxides. Trucks and buses using these devices released up to 70 percent more pollution than "legal" vehicles (Mark and Morey, 2000). In 1998 alone, engines equipped with defeat devices may have polluted the air with an additional 1.3 million tons of nitrogen oxides—equivalent to the pollution produced by 29 million cars. Manufacturers agreed to stop using these devices and pay more than $1 billion for corrective action, future improvements, and fines in a 1998 settlement with the EPA and the California Air Resources Board. It was the largest settlement ever reached by an EPA enforcement action.

Monitoring the in-use performance of emission controls is critical to ensuring that vehicles remain cleaner throughout their useful lives. Inspection and maintenance (I/M) programs can help reduce excess emissions from high-polluting gasoline and diesel vehicles, but most, if not all do not currently include diesel cars and trucks. If diesel vehicles become a larger portion of the U.S. fleet, they will need to be evaluated as part of I/M. The diesel industry's past use of air pollution defeat devices, combined with the technical difficulties of developing pollution controls for nitrogen oxides, point to the need for targeted monitoring of new diesel vehicles, particularly during their first decade of use.

PARTICULATE MATTER (SOOT)

Soot is released directly from the tailpipe or may form as a secondary particle when nitrogen oxides, hydrocarbons, and sulfur oxides released from the tailpipe react in the atmosphere. Nearly all of the soot particles produced by gasoline and diesel vehicles are small enough to be inhaled deep into the lungs. The EPA estimates that highway vehicles contribute about two percent of all fine particulates (EPA, 2003b), but the share in urban areas is often much higher.[21] In the Los Angeles basin, for example, highway vehicles are estimated to release 11 percent of manmade fine particulates (CARB, 2003).

Numerous public health studies have linked particulate pollution to asthma hospitalizations, chronic bronchitis, heart disease, and premature death (EPA, 2002). Sensitive populations including children, the elderly, asthmatics, and individuals with pre-existing respiratory or cardiovascular diseases are at the greatest risk from exposure to particulates.

Soot has also been directly linked with premature death. A recent study evaluated the health of about 500,000 people in more than 100 U.S. cities over a period of 16 years (1982 to 1998)—long enough for slow-developing diseases, such as lung cancer and heart disease, to appear (Pope et al., 2002). The study found that the higher the level of particulates in the air, the greater the risk of dying from lung cancer, heart disease, or any other cause.[22]

Another study of more than one million adults in 151 U.S. cities found that higher concentrations of fine particulates were associated with a 17 percent increase in total mortality (Pope et al., 1995). Even higher mortality rates—a 26 percent increase in total mortality—were associated with fine particulates in a study of more than 8,000 people living in six eastern U.S. cities

21 Fine particulates are defined as having a diameter of 2.5 microns or smaller, known as PM2.5.

22 The study found that the risk of lung cancer death went up eight percent for every 10 micrograms of fine particles in a cubic meter (roughly three feet by three feet) of air. Heart disease deaths went up six percent and deaths from all causes went up four percent for each such increase.

(Dockery et al., 1993). Based on these studies and other research, the EPA estimates that new standards regulating emissions of fine particulates will save 15,000 lives every year (EPA, 1997).

Finally, a recent report by Germany's Environmental Agency estimates that between 8,000 and 16,000 people die prematurely in Germany every year—one to two percent of all deaths—from exposure to diesel exhaust (Wichmann et al., 2003). Experts predict the use of advanced aftertreatment technologies to reduce vehicular soot will extend the life expectancy of every German by one to three months.

Today's cars

Recent studies show that the average diesel passenger vehicle releases 17 to 40 times more soot than a gasoline vehicle from the same model year (Table 4). Unfortunately, the diesel vehicles evaluated in these studies are now more than 15 years old, and there is scant information available on the soot released by today's light-duty diesel engines. Much more information is available on the heavy-duty sector, where most of the nation's diesel fuel is consumed. Though approximately three times more gasoline is consumed in the United States than diesel fuel, the EPA nevertheless estimates that total particulate emissions from heavy diesel-powered trucks and buses are more than double those from gasoline-powered cars and light trucks (EPA, 2003).

Tomorrow's cars

Both diesel and gasoline cars should be able to meet the Tier 2 standards for particulate pollution. In fact, recent studies find that well-functioning particulate traps for diesel vehicles can reduce soot to very low levels (Ecotraffic, 2002; Ayala et al.,

Table 4 **Particulate Emissions from Gasoline and Diesel Cars and Light Trucks**

		Central Carolina Vehicle Particulate Study[a]		Denver Study[b]	
Model Year Range	**Fuel**	**Summer Average (grams per mile)**	**Winter Average (grams per mile)**	**Number of Vehicles**	**Average (grams per mile)**
Pre–1985[c]	Gasoline	0.0196	0.0694	35	0.0429
1985–1989[d]	Gasoline	0.0173	0.0260	33	0.0144
1990–1992[e]	Gasoline	0.0053	0.0243	61	0.0025
1993–1997[e]	Gasoline	0.0046	0.0078		
Average	Gasoline	0.0106	0.0276	129	0.0165
Average excluding high emitters	Gasoline	0.0079	0.0133		
1977–1989	Diesel	0.4871	0.3757	18	0.5610

NOTES:

a. The Central Carolina Vehicle Particulate Study (Cadle, 2001) collected emissions from 120 gasoline and 5 diesel vehicles in the summer. For the winter tests, the study analyzed 119 gasoline and 3 diesel vehicles in the winter. The vehicles were tested on a chassis dynamometer with the IM240 driving cycle, which is a test cycle for warmed-up vehicles. This study found that gasoline "high emitters," defined as vehicles releasing 100 mg/mile, had a significant impact on emissions. There were eight high emitters in the winter phase and one in the summer phase. Excluding high emitters from the emissions data lowered the average emissions between 14% and 25%.

b. The Denver study (CRC, 1998) tested a total of 129 gasoline vehicles and 19 diesel vehicles. The vehicles were tested using the federal test procedure (FTP), which does not account for the impact of seasonal temperature fluctuations on emissions. The study found that 30% of the gasoline vehicles were "high emitters," defined as Tier 1 vehicles releasing 1.5 times the certified hydrocarbon, carbon monoxide, or nitrogen oxide emission levels (different criteria were specified for Tier 0 vehicles).

c. For the Denver Study, the model year range should be "Pre-1986".

d. For the Denver Study, the model year range should be "1986–1990".

e. For the Denver Study, the model year range should be "1991–1997".

Table 5 **Toxic Air Contaminants in Diesel Exhaust**[a]

acetaldehyde	inorganic lead
acrolein	manganese compounds
aniline	mercury compounds
antimony compounds	methanol
arsenic	methyl ethyl ketone
benzene	naphthalene
beryllium compounds	nickel
biphenyl	4-nitrobiphenyl
bis[2-ethylhexyl]phthalate	phenol
1,3-butadiene	phosphorus
cadmium	polycyclic aromatic hydrocarbons (PAHs)
chlorine	polycyclic organic matter
chlorobenzene	propionaldehyde
chromium compounds	selenium compounds
cobalt compounds	styrene
creosol isomers	toluene
cyanide compounds	xylene isomers and mixtures
dibutylphthalate	m-xylenes
dioxins and dibenzofurans	o-xylenes
ethyl benzene	p-xylenes
formaldehyde	

SOURCE: California Air Resources Board, 1998.

NOTE:
a. According to the California Health and Safety Code, a "toxic air contaminant" is "an air pollutant which may cause or contribute to an increase in mortality or in serious illness, or which may pose a present or potential hazard to human health."

Table 6 **Cancer Risk Assessments of Diesel Exhaust**

Year	Organization	Conclusion
2002	U.S. Environmental Protection Agency	Likely human carcinogen
2001	Americal Council of Government Industrial Hygienists (proposal)	Suspected human carcinogen
2001	U.S. Department of Health and Human Services	Reasonably anticipated to be a human carcinogen
1998	California Air Resources Board	Toxic air contaminant
1996	World Heath Organization International Programme on Chemical Safety	Probable human carcinogen
1995	Health Effects Institute	Potential to cause cancer
1990	State of California	Known to cause cancer
1989	International Agency for Research on Cancer (IARC)	Probable human carcinogen
1988	National Institute for Occupational Safety and Health (NIOSH)	Potential occupational carcinogen

2002).[23] The key will be monitoring the in-use performance of these control systems, which may have higher rates of degradation and failure, especially during the early years of implementation.

AIR TOXICS

The health impact of toxic air contaminants varies from pollutant to pollutant, but in each case, the damage can be serious. People exposed to air toxics at sufficient concentrations and durations may have an increased chance of developing cancer or other serious conditions including damage to the immune system and neurological, reproductive, developmental, or respiratory problems.

There is a weighty body of evidence that diesel exhaust is toxic to human health (Table 5). More than 30 epidemiological studies have found that people exposed to diesel exhaust are at greater risk of lung cancer (CARB, 1998), and a host of federal and international agencies have concluded that diesel exhaust is a known, probable, or likely carcinogen (Table 6).

A landmark study of air toxics in Los Angeles concluded that diesel soot is responsible for more cancer cases than pollutants from gasoline engines (SCAQMD, 2002).[24] Specifically, particulates

23 A more pessimistic analysis by the EPA suggests diesel cars will continue to release more particulates than gasoline cars, even under the new Tier 2 standards. If diesel vehicles comprised nine percent of the new car market and 24 percent of the new truck market, for example, particulate pollution from light-duty vehicles would increase from at least 19 percent in the best-case analysis to 38 percent for the worst case.

from diesel engines contributed about 70 percent of the cancer risk from airborne pollution, while the air toxics from all other mobile sources contributed 20 percent of the cancer risk. A statewide study found similar results (CARB, 2000). Though California drivers use six times more gasoline than diesel, the cancer risk from gasoline vehicles is a fraction of the risk from diesel vehicles.

While the toxicity of diesel has been well researched, there is relatively little information on the toxicity of gasoline. New studies indicate that today's average gasoline and diesel vehicles have the same toxicity per unit of mass (Seagrave et al., 2002), but the exhaust from high-emitting gasoline engines may be more toxic.

Today's cars

Conventional diesel cars release significantly more air toxics per mile traveled than comparable gasoline models. The relative toxicity of gasoline and diesel exhaust, particularly from the current generation of engines, requires further research.

Tomorrow's cars

Early studies suggest that well-functioning particulate traps reduce both the mass and toxicity of diesel exhaust (Ayala et al., 2002; Ecotraffic, 2002). This is encouraging news, and underscores the potential for Tier 2 emission controls to reduce toxicity and mass simultaneously. Unfortunately, there is no information available on the toxicity of gasoline and diesel exhaust for Tier 2-compliant engines. To evaluate whether the Tier 2 standards are adequate for addressing public health concerns about toxicity, more studies measuring in-use emissions of air toxics and evaluating their impact on human health must be conducted.

24 Individual pollutants from gasoline exhaust evaluated in the study include 1,3-butadiene, benzene, formaldehyde, and acetaldehyde.

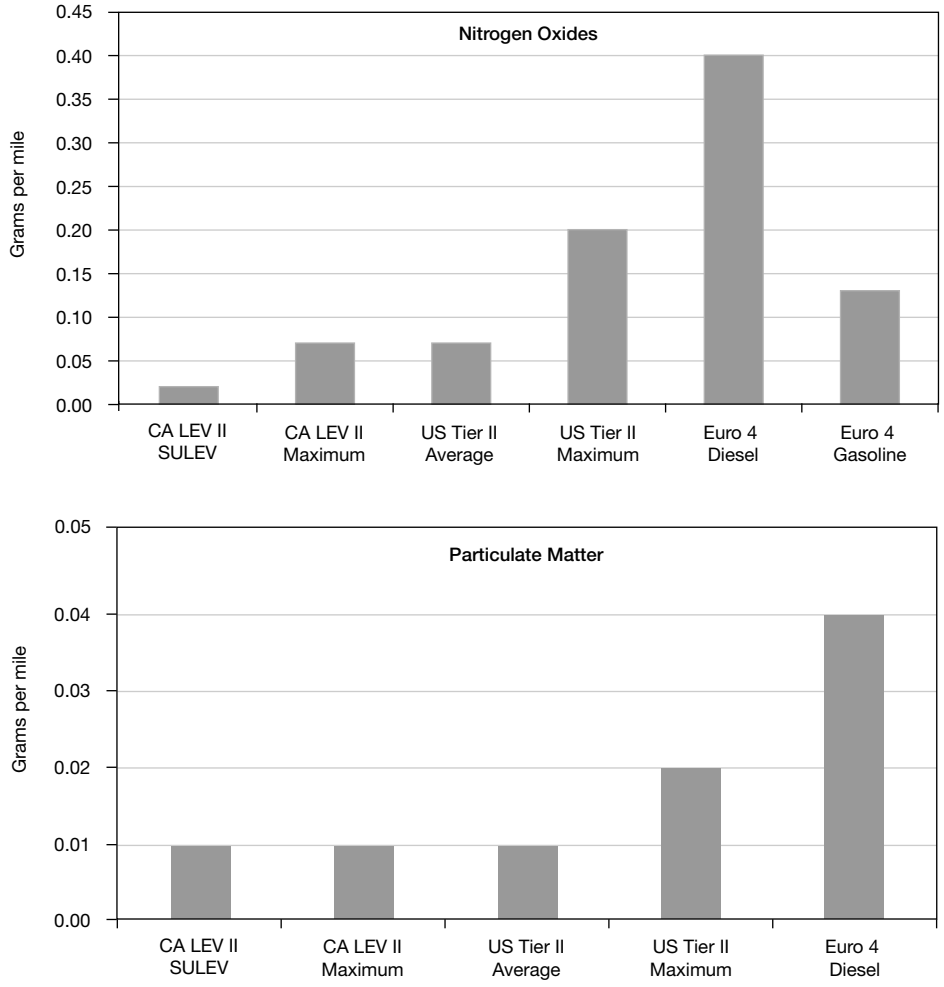
Chapter 4

What Do Emissions Standards Really Mean?

U.S. emissions standards such as the Tier 1 standards in effect between 1994 and 2003 have historically permitted diesel vehicles to release more smog-forming pollution and soot than their gasoline counterparts. New standards are closing the gap.

Modeled after California's tailpipe regulations (called "LEV II"), new federal Tier 2 emissions standards will hold light-duty diesel vehicles to the same set of standards as gasoline cars starting in 2004. Unfortunately, the tiered structure of these standards allows manufacturers to continue selling cars with high emissions, especially through 2009 (Figure 12). Europe is also considering more stringent diesel standards, using the U.S. standards as a model.

Figure 12 **New Tailpipe Emissions Standards for Passenger Cars**



SOURCE: Emissions standards from DieselNet, no date.

One possible flaw in all of the current emissions standards is that they are based solely on mass and do not address particle size or toxicity. It remains to be seen whether mass-based emissions standards are sufficient to protect human health from the very small particles, which could penetrate more deeply into the lungs, and air toxics, such as benzene and dioxin, that are released from the tailpipe.

FEDERAL TAILPIPE STANDARDS

Under today's Tier 1 tailpipe standards, diesel cars and trucks are allowed to release two times more nitrogen oxides than gasoline vehicles. And although diesel cars are allowed to release ten to several hundred times more particulate matter than the actual emissions from gasoline cars and trucks, they have struggled to meet even this standard. (There are no particulate standards for gasoline cars, primarily because properly operating three-way catalysts effectively reduce soot to very low levels).

The new Tier 2 standards that will be phased in between 2004 and 2009 (Figure 13) require all diesel vehicles—cars, minivans, light-duty trucks, and SUVs alike—to meet the same set of emissions standards as gasoline vehicles.

However, because Tier 2 standards allow for "fleet averaging," automakers can continue selling vehicles that emit higher levels of pollution as long as their fleet average for nitrogen oxide emissions falls below a specified value (0.07 g/m when the

Table 7 **Tier 2 Tailpipe Emissions Standards (grams per mile)**[a]

Bin#	Particulate Matter (PM)	Nitrogen Oxides (NOx)	Non-Methane Organic Gases (NMOG)	Formaldehyde (HCHO)	Carbon Monoxide (CO)	Notes
11	0.12	0.9	0.28	0.032	7.3	b
10	0.08	0.6	0.156 (0.230)	0.018 (0.027)	4.2 (6.4)	c,d,e
9	0.06	0.3	0.09 (0.180)	0.018	4.2	c,d,f
Above bins are temporary and will expire in 2006 (for cars and light light-duty trucks) and 2008 (for heavy light-duty trucks)						
8	0.02	0.2	0.125 (0.156)	0.018	4.2	d
7	0.02	0.15	0.09	0.018	4.2	
6	0.01	0.1	0.09	0.018	4.2	
5	0.01	0.07	0.09	0.018	4.2	
4	0.01	0.04	0.07	0.011	2.1	
3	0.01	0.03	0.055	0.011	2.1	
2	0.01	0.02	0.01	0.004	2.1	
1	0.01	0	0	0	0	

NOTES:

a. Standards apply to the full useful life of the vehicle (120,000 miles).

b. Restricted to medium-duty passenger vehicles (MDPV) only; expires after model year 2008. MDPV refers to a new class of medium-duty passenger vehicles including larger SUVs and passenger vans. These vehicles have a gross vehicle weight (GVW) rated between 8,500 and 10,000 pounds when used for personal transportation. Engines in commercial vehicles above 8,500 GVW, such as cargo vans and light trucks, will continue to be certified according to heavy-duty emissions standards. For diesel MDPVs prior to 2008, the EPA is offering manufacturers the option of meeting the heavy-duty engine standards rather than the Tier 2 standards. In 2008, manufacturers must chassis-certify diesel vehicles and bring them into Tier 2 or an interim program. In 2009 and beyond, all MDPVs (including diesels) must meet the Tier 2 standards.

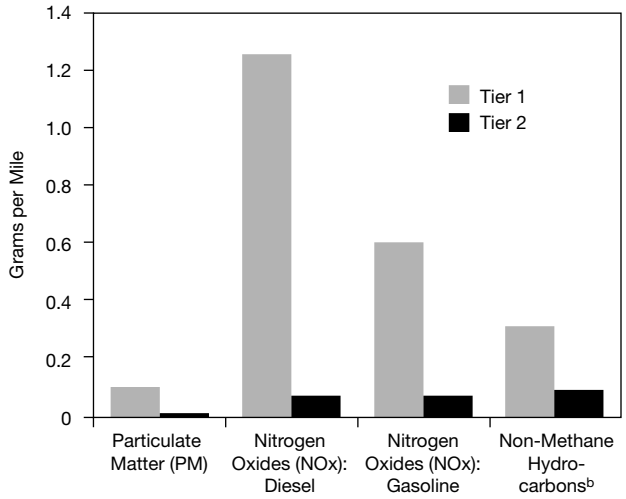
c. Bin deleted at end of 2008 for heavy light-duty trucks (HLDTs) and 2006 for all other light-duty passenger vehicles.

d. Higher temporary NMOG, CO, and HCHO values apply only to HLDTs and expire after 2008.

e. Optional temporary NMOG standard of 0.28 applies for qualifying Class 4 light-duty trucks (LDT4s) and MDPVs only.

f. Optional temporary NMOG standard of 0.13 applies for qualifying Class 2 light-duty trucks (LDT2s) only.

Figure 13 **U.S. Average Tailpipe Emissions Standards: Old (Tier 1) vs. New (Tier 2[a])**



NOTES:
a. Fully implemented Tier 2 average emissions equal Bin 5.
b. For Tier 2, the standard applies to non-methane organic gases (NMOG).

standards are fully implemented). All passenger vehicles must be certified at one of eight emission levels called "bins" by 2009 (Table 7). These bins are meant to give the manufacturers flexibility in meeting the standards, while ensuring that average emissions remain at or near the Bin 5 level.

This flexibility has the downside of clearing the way for certain cars to release more toxic soot and nitrogen oxides. For example:

- All passenger vehicles can continue to release higher levels of pollutants during the phase-in period between 2004 and 2008.
- Through MY 2006, diesel cars can emit up to 0.08 g/m of soot, only a modest improvement over the current standard of 0.1 g/m.
- Heavier trucks are given even more leeway, and do not have to start meeting their final Tier 2 targets until 2008.
- Once the standards are fully implemented, cars certified at higher (dirtier) bins can continue to release up to two times more soot and nearly three times more nitrogen oxides than the average new car.

Despite the fact that no diesel car has yet been certified at any of the final standards (though some have qualified for Bin 10, the weakest of the temporary tiers), diesel cleanup technologies are being rapidly developed. Particulate traps are already available on certain diesel cars in Europe and seem to be performing well. Nitrogen oxide controls for diesel vehicles are still in the development stage, and currently pose the greatest challenge to manufacturers. With the advent of low-sulfur diesel fuel in late 2006, some automakers are confident that they will be able to meet the Tier 2 challenge, perhaps even the fleetwide average tier (Bin 5). Several have demonstrated prototype diesel cars that are within reach of Bin 8 and Bin 5. The question now is whether diesel vehicles will be able to certify to the lowest (cleanest) bins.

CALIFORNIA TAILPIPE STANDARDS

California has historically led the nation and the world in developing strict tailpipe standards for cars and trucks. The state's Low Emission Vehicle II (LEV II) standards, passed in 1998, have been adopted by Maine, Massachusetts, New York, and Vermont. Together, these states account for more than one-fifth of all new car sales in the United States.

Like the federal Tier 2 program, LEV II standards hold light trucks and cars, whether powered by diesel or gasoline, to the same limits on tailpipe emissions (Table 8, pg. 30).[25] California also allows fleet averaging, but focuses on

25. The distinction between cars and light trucks is maintained for calculating fleetwide non-methane organic gas averages and some evaporative emissions standards, but is removed for tailpipe standards. Light-duty passenger vehicles, as defined by California, have a gross vehicle weight under 8,500 pounds.

Table 8 **California's LEV II Car and Truck Tailpipe Emissions Standards (grams per mile)**

Category	Particulate Matter (PM)	Nitrogen Oxides (NOx)	Non-Methane Organic Gases (NMOG)	Formaldehyde (HCHO)	Carbon Monoxide (CO)
Passenger Cars and Light-Duty Vehicles (gross vehicle weight rating <8,500 pounds)					
Low Emission Vehicle (LEV)	0.01	0.07	0.09	0.018	4.2
Ultra Low Emission Vehicle (ULEV)	0.01	0.07	0.055	0.011	2.1
Super Ultra Low Emission Vehicle (SULEV)	0.01	0.02	0.01	0.004	1.0
Medium-Duty Vehicles (gross vehicle weight rating 8,500–10,000 pounds)					
LEV	0.012	0.2	0.195	0.032	6.4
ULEV	0.06	0.2	0.143	0.016	6.4
SULEV	0.06	0.1	0.1	0.008	3.2

California's Zero Emission Vehicle (ZEV) program

In addition to its tailpipe standards, California promotes cleaner cars and trucks through its ZEV program, which has undergone several modifications over the last several years and will now go into effect for MY 2005 vehicles. Under the program, a percentage of each automaker's sales must be zero or near-zero emitting vehicles.

Partial ZEV (PZEV) credit is given to vehicles that meet SULEV requirements for a durability life of 150,000 miles, have zero evaporative emissions, and have an extended performance and defects warranty. Vehicles that include technological components that advance pure ZEVs, known as advanced technology PZEVs (AT-PZEVs), are awarded extra credits. In addition, large manufacturers are required to sell a certain amount of zero emission vehicles (ZEVs) in the coming years. Two compliance pathways exist that allow for a mixture of battery-electric vehicles or fuel cell vehicles (ZEVs), AT-PZEVs, and PZEVs.

hydrocarbons rather than nitrogen oxides. These standards begin taking effect in 2004 and will be fully implemented by 2007—two years ahead of the federal program.

By that time, most cars and trucks sold in California must be at least as clean as vehicles meeting the federal fleetwide average for 2009 (Bin 5),[26] and some must be even cleaner (see box, "California's Zero Emission Vehicle (ZEV) program"). Tier 2 standards allow twice the particulates and nearly three times more nitrogen oxides than LEV II,[27] and California's *maximum* allowable amount of nitrogen oxide emissions is equal to the *average* federally certified vehicle (Figure 12, pg. 27).

Yet even California's stringent standards feature a loophole that allows cars and trucks to pollute more than the standards dictate. An antiquated law passed in 1981 (Assembly Bill 965) allows car dealers to sell "specialty" vehicles that meet federal, but not state, tailpipe emission require-

26 There is only one category of engines, medium-duty passenger vehicles (gross vehicle weight between 8,500 and 10,000 pounds), allowed to release more particulates under LEV II than the federal Tier 2 standards. A medium-duty passenger vehicle certified as a super ultra-low emission vehicle (SULEV) under LEV II could emit three times more particulates than under Tier 2 (0.6 g/m versus 0.2 g/m). California also allows diesel passenger vehicles above 8,500 pounds to certify under the heavy-duty vehicle standards, which are, in general, more lenient than the standards for medium-duty vehicles. Finally, LEV II permits manufacturers to certify up to four percent of their light-duty truck fleet (trucks with a carrying capacity greater than 2,500 pounds) to a weaker nitrogen oxide standard. Despite the fact that nitrogen oxide emissions can be about 40 percent higher for these vehicles (0.1 g/m versus 0.07 g/m), this gift to automakers is still twice as strict as the federal Bin 8 standard (0.2 g/m).

27 For vehicles with a gross vehicle weight of 8,500 pounds or less.

ments. At the time the law passed, the legislature assumed only a small volume of vehicles would qualify, but this has not been the case. The law has been used extensively, at times accounting for up to eight percent of vehicle sales in the state.

The excess emissions from these vehicles are supposed to be offset by the remaining vehicle fleet, but it is not clear whether these offsets have occurred in the real world or only on paper.[28] Furthermore, because the offsets are based on standards rather than actual emissions, pollution would increase should diesel cars and trucks apply for the exemption.[29]

EUROPEAN TAILPIPE STANDARDS

The new European emissions standards (called "Euro 4") will allow the average car to release up to four times more soot and six times more nitrogen oxides from its tailpipe than U.S. Tier 2 standards permit (Figure 12). And, unlike the U.S. or California standards, Euro 4 continues to allow diesel cars and trucks to emit higher levels of soot and nitrogen oxides: 2.5 times more particulates and greater than three times more nitrogen oxides than the Tier 2 average.

It should also be noted that the regulated "useful life" of a European vehicle is one-third to one-half as long as that mandated by the U.S. EPA.[30] Because useful life determines how long manufacturers must guarantee their emission control systems, European systems would not last long enough to meet American durability requirements—that is, if they could meet the tougher U.S. emissions standards at all. European test cycles and protocols, moreover, are less rigorous than in the United States, so the actual gap between American and European emissions is even greater than the standards indicate.

Some European countries have launched a serious push to tighten diesel emissions standards, as exemplified by France and Germany's appeal to the European Union's environment commissioner. The two countries pointed out that the recent doubling of the European diesel car fleet will produce 60 percent more particulate emissions by 2020 than previously projected, and that these cars discharge 8 to 10 times more nitrogen oxides than a gasoline vehicle (UBA, 2003). Environmental and public health groups are also applying pressure on the European Union to tighten its standards.

PARTICLE SIZE AND TOXICITY

Our current pollution standards do not address particle size or toxicity, which lie at the heart of many public health concerns about soot. A growing body of evidence suggests that fine particles may contain more of the reactive substances linked with serious health risks than coarse particles (EPA, 2000b). These smaller particles may penetrate more deeply into the respiratory tract, where their large surface-to-volume ratio could allow for more biological interaction.

Modern engines produce smaller particles, possibly in greater numbers than older models, but the exact roles gasoline and diesel engines

28 A.B. 965 only allows offsets for exceeding hydrocarbon and nitrogen oxide tailpipe standards. Particulate matter standards cannot be offset.

29 Because CARB's current regulations for the offset exceptions are based on standards rather than actual emissions, more toxic soot will be released into the air if non-complying diesel cars are allowed to use offsets from gasoline cars. Today's diesel passenger vehicles generally emit 10 to greater than 40 times more PM10 (particles with a diameter of 10 microns or less) from the tailpipe than gasoline vehicles, and until LEV II is fully implemented in 2007, diesel cars can meet the weaker LEV I particulate standard (0.08 g/m instead of 0.01 g/m). CARB and others have determined that diesel exhaust is a toxic air contaminant, so any increases in particulate emissions carry public health consequences. Even when LEV II is fully implemented, four percent of trucks can meet a weaker nitrogen oxide standard.

30 The new Euro 4 standards require engines to be certification tested at roughly 60,000 miles—half the regulatory useful life of U.S. Tier 2 vehicles (which are tested at 120,000 miles).

play in the generation of fine particulates (less than 2.5 microns in diameter, or about 1/40 the thickness of a human hair), ultrafine particles (less than 0.1 microns in diameter) and nanoparticles (less than 0.05 microns in diameter) are still unknown. Recent European measurements indicate that gasoline spark-ignited engines running at high speed and load may release as many or more nanoparticles as typical diesel engines (Kittleson et al., 2003). Unfortunately, because it is not yet clear whether today's technology can accurately measure nanoparticles and there is no accepted testing method to ensure consistent measurement, comparisons between different studies are nearly impossible (Andersson, 2001). Different transient cycles, operating conditions, and exhaust temperatures also affect nanoparticle generation.

Since regulations governing soot emissions are based on particle mass, not size or toxicity, stricter regulations may not reduce public health risks proportionally.

IN-USE PERFORMANCE

The primary method for evaluating the in-use performance of emission controls, I/M programs, came under fire in a recent report by the National Research Council (NRC, 2001), which concluded that these programs have performed far more poorly than expected—meeting between zero and 50 percent of their expectations. Part of the problem is that the models used to predict performance were flawed; rather than using real-world, empirical (observational) data, the models relied on oversimplified and incorrect assumptions. As with the Smog Check programs currently under way in areas of the country suffering from poor air quality, the NRC recommended that all I/M programs focus on targeting and repairing high-emitting vehicles, which are responsible for the bulk of excess emissions.

Diesel cars and trucks have historically been exempted from the requirements of I/M programs, and this loophole could have drastic consequences if diesel claims a larger share of the nation's vehicle fleet. Diesel pollution controls currently under development could have higher failure rates as they enter the fleet for the first time, and, without sufficient oversight, may ultimately pollute at levels above the federal standards.

To be sure emissions standards achieve their goals, real-world pollution data and in-use monitoring are needed. Studies that evaluate real-world pollution can supplement and support I/M programs. Monitoring whether new diesel pollution controls are functioning properly and whether gasoline vehicles are performing at their certification levels is critical to ensuring that the new Tier 2 standards live up to their potential.

Chapter 5
Smart Public Policies

Our nation needs to reverse a two-decade trend of falling fuel economy and rising oil imports, protect public health, reduce heat-trapping gases, and invest our public and private funds wisely—all at the same time. Our analysis suggests this is realistic. Better conventional and hybrid-electric gasoline cars provide cost-effective reductions in oil use, heat-trapping gases, and air pollutants. Diesel vehicles, although not as cost-effective, can also play a role in reducing oil use and heat-trapping gases. The key unanswered question is whether diesel vehicles will ever be able to deliver the progress on air pollution that efficient modern gasoline technology can achieve today.

Smart public policies can shift the direction of our transportation system away from a future of hotter climates, smog-choked cities, and energy insecurity, but it will take consumers, automakers, researchers, and governments all working together to point the way. With enough political will, we can get cars that promote public health, energy security, and a better environment out of the showrooms and laboratories and into the waiting hands of consumers.

TO PROTECT PUBLIC HEALTH

1. Maintain new emission levels

At a minimum, the EPA needs to fully implement the new Tier 2 standards coming into effect between 2004 and 2009. Some gasoline cars already meet the cleanest Tier 2 standards, which the EPA estimates will prevent as many as 4,300 deaths, more than 10,000 cases of chronic and acute bronchitis, and tens of thousands of respiratory problems each year (EPA, 1999). There is no need to sacrifice public health by weakening these standards.

2. Re-evaluate standards

Because current tailpipe standards are based on mass rather than toxicity, particle size, or number, additional research is needed to determine whether the Tier 2 standards protect public health sufficiently. Some European countries including Sweden and Germany are exploring the addition of particle number to tailpipe regulations. As cleanup technologies reduce the total mass of pollution, other factors may figure more prominently as health risks, so we need to better understand how pollution controls may alter the exhaust profile—and the attendant impact on public health—of Tier 2-compliant vehicles.

3. Improve particle measurement techniques

A key to evaluating the effectiveness of current emissions standards is standardized measurement and evaluation techniques. However, techniques for measuring very small particles and evaluating their toxicity are still in development, and there are few ways to ensure consistent and accurate results. Government, industry, and research institutions need to support research and development in this area.

4. Improve real-world measurements

Monitoring the in-use performance of emission controls is critical to evaluating whether real-world pollution matches engine certification, and whether current programs are sufficient to keep vehicles cleaner over their lifetime of use. Gasoline

high emitters, for example, may contribute greater than 50 times more pollution than engine certification tests indicate. And new pollution controls for diesel engines may suffer from higher rates of failure.

It will be particularly important to monitor the performance of gasoline and diesel vehicles during the first decade Tier 2 standards are in place in order to verify the cleanliness of gasoline vehicles and that diesel pollution controls are working well, allowing diesel to move beyond its "dirty" image. A key first step is researching and developing technologies to measure in-use emissions, which will support the design of better technology and control programs.

5. Implement effective I/M programs

I/M programs can help ensure that tailpipe standards are achieving real-world emission reductions, but at the moment, only areas suffering from serious air quality problems have such programs built into their state air quality plans. The benefits of these local I/M programs tend to be minimized by the fact that high-emitting vehicles are found in all areas of the country. In addition, because the models used by these programs to estimate on-road emissions and predict program effectiveness are flawed, most I/M programs are not achieving the expected results. Incorporating real-world observational data into the models would improve program effectiveness.

Diesel vehicles, it must be noted, are excluded from most, if not all, I/M programs. This must change if diesel gains a larger share of the market. Finally, ensuring that low-income families receive the support they need to either repair or replace a high-emitting vehicle is also critical to the success of I/M programs.

TO PROMOTE ENERGY SECURITY

1. Raise fuel economy standards

Some members of Congress and industry see growth in diesel sales as a way to increase the fuel economy of cars and trucks without having to reopen the contentious debate about CAFE standards.

While diesel and gasoline vehicles have significant potential to improve fuel economy, many of the necessary efficiency technologies will end up in manufacturers' fleets without their fuel economy benefits ever being realized. History has shown that automakers continue to use similar technologies merely to increase vehicle weight and power, bypassing opportunities that would improve fuel economy, save customers money at the pump, and maintain or improve vehicle safety. Raising fuel economy standards will ensure that consumers are offered a wide variety of fuel-efficient choices.

2. Eliminate inequities in standards

CAFE standards give credit to gasoline and diesel vehicles based on fuel economy, not oil use. As noted earlier, it takes more oil to make a gallon of diesel than a gallon of gasoline. To reduce oil use, a diesel vehicle would have to achieve at least 25 percent higher fuel economy (or 10 percent in gasoline-equivalent units) than its gasoline counterpart.[31] Because CAFE is based on fuel economy and not energy content or oil use, more diesel vehicles on the road could have the perverse effect of increasing U.S. oil dependence.[32] To correct this problem, the inequities in how gasoline and

31 UCS calculation based on Wang, 2003. Assumes no rebound effect from higher fuel economy.

32 CAFE is an averaging system. This allows an automaker to meet the current 20.7 mpg light-truck standard despite switching its production from two 20.7 mpg vehicles to one 28 mpg diesel vehicle and one 17 mpg gasoline vehicle. Ironically, the result of this switch would be an increase in oil demand of about eight percent. Over their useful lives, the two 20.7 mpg gasoline light trucks would each consume about 243 barrels of oil (486 total). The 17 mpg gasoline vehicle would require 296 barrels and the 28 mpg diesel vehicle would require 230, for a total of 526—an eight percent increase in oil demand.

diesel are treated under CAFE should be eliminated. At a minimum, the CAFE program should be changed to compare gasoline and diesel on an equivalent energy basis (gallons of gasoline equivalent).

TO AVOID PUBLIC HEALTH TRADEOFFS

1. Reduce heat-trapping gases safely

In July 2002, former California Governor Gray Davis signed groundbreaking legislation directing the state Air Resources Board to develop regulations for limiting heat-trapping gas emissions from passenger cars and trucks. Some stakeholders, using Europe's preference for diesel cars as a model, have suggested increasing California's use of diesel as a way to reduce heat-trapping gases. However, public policies for reducing heat-trapping gas emissions must also protect public health, and until diesel vehicles demonstrate that they are cleaner than the average new car meeting California's final LEV II standards, they should not be pushed to the forefront.

Regulators may even need to go beyond LEV II and seek tighter air pollution standards to deliver truly healthy air, which will prove a significant challenge for diesel. Long-term success in meeting the state's environmental and health goals will hinge on technologies that can deliver deep cuts across the board.

2. Provide incentives for better vehicles

A variety of federal and state incentives can help put cleaner, more fuel-efficient vehicles on the road. Incentives are particularly important the first few years that a new technology, like hybrid-electric vehicles, is available on the market. These incentives can increase production volumes and therefore bring down costs while also helping consumers become more familiar with a new technology. And, because protecting public health and increasing fuel economy should be complementary goals, any incentives to promote fuel-efficient vehicles must require that tailpipe emissions be lower than the Tier 2 average.

Diesel and conventional gasoline vehicles should compete on a level playing field for incentive funds. Unlike hybrids, which offer a link to future vehicles powered by hydrogen fuel cell technology, conventional diesel vehicles do not offer significant advantages over gasoline vehicles in reaching a specific fuel economy goal, and they may come with an emissions disadvantage.

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Appendix A
Diesel Cleanup Technologies

Diesel cleanup technologies are advancing rapidly, and some researchers are optimistic that high-efficiency systems are close to realization (see Johnson, 2003 for a review of recent progress in diesel emission controls). Emissions from diesel cars and trucks can be reduced through a combination of engine improvements, fuel formulation changes, and exhaust control equipment (also known as aftertreatment).

Most of the technologies needed to close the gap between gasoline and diesel vehicles are still in the experimental stage, and have not been fully tested under real-world conditions. Some of these technologies involve a fuel economy penalty or can create new and unintended pollution problems. The most serious challenges for diesel engine manufacturers are to reduce nitrogen oxides and optimize systems to cut pollution while simultaneously maintaining desired performance characteristics.

ENGINE IMPROVEMENTS

Engine-out pollution can be reduced by carefully managing fuel combustion. Key engine management strategies to reduce emissions include advanced fuel injection, the recirculation of exhaust gases, the addition of advanced turbochargers, and the replacement of conventional diesel engines with homogenous-charge compression-ignition engines.

Fuel injection

Current-generation diesel engines inject fuel directly into the cylinders, a process known as direct injection (DI). Past-generation diesel engines relied on indirect injection, in which the fuel and air were mixed in a chamber before being injected into the cylinders. This premixing in indirect-injection engines resulted in energy losses and a fuel economy penalty. The efficiency advantage of direct injection has translated into higher fuel economy, but one unintended consequence is more soot pollution.

Fuel-rich areas in the combustion chamber lead to pockets of unburned fuel and particulate emissions. Fuel injection technologies under development to improve both engine and emissions performance include high-pressure fuel injection, such as hydraulic electronic unit injection (HEUI)

Table A-1 **Strategies for Cleaning Up Diesel Engines**

Engine Improvements	Pollutants Controlled
Hydraulic electronic unit injection (HEUI)	PM
Common rail fuel injection	NOx & PM
Advanced electronic controls	NOx & PM
Exhaust gas recirculation	NOx
Variable geometry turbochargers	NOx & PM
Electronic superchargers	NOx
Homogenous charge compression ignition	PM & NOx
Fuel and Oil Specifications	
Sulfur content of fuel	PM
Biodiesel	PM
Lubrication oil	PM
Exhaust Control Equipment	
Oxidation catalyst	PM
Particulate traps	PM
Lean NOx catalysts	NOx
NOx adsorbers	NOx
Selective catalytic reduction	NOx & PM

Table A-2 **Advanced Diesel Aftertreatment Technologies: Prospects and Issues**

	Pollution Reduction Potential					
Technology or Fuel	**Particulate Matter**	**Nitrogen Oxides**	**Fuel Economy Penalty**	**Issues**	**Low-Sulfur Fuel Requirement**	**Stage of Development**
Continuously regenerating ("passive") particulate trap[1]	85% or more		Up to 2%	Current generation results in more smog-forming nitrous oxide (NO_2) emissions; more work is needed to improve filter regeneration, reduce back pressure, and manage lube oil ash	Yes	Optimization stage
Active particulate trap[1]	85% or more		Up to 5% or more	Fuel economy penalty can be high; more work is needed to improve filter regeneration, reduce back pressure, and manage lube oil ash	No, though the higher-sulfur fuel may cause reduced system life and decreased fuel economy	Optimization stage
Oxidation catalyst[2]	20% to 50%		None	Emission reductions may not be sufficient to pass Tier 2	No	Currently used in United States on Volkswagen diesel cars
Exhaust gas recirculation[3]		Up to 50%	Up to 5%	May be incompatible with certain advanced aftertreatment technologies; may increase particulate pollution and engine wear	No, though the higher-sulfur fuel may cause greater engine wear	Currently available on light-duty diesel engines
Lean NOx catalyst[4]		25% today 50% to 70% emerging	2% to 6%	Potential for hydrocarbon slip; emission reductions may not be sufficient to pass Tier 2	Yes	Under development
NOx adsorber or "trap"[5]		80% to 95%	2% to 6%	Durability concerns; higher cost than other alternatives	Yes	Under development
Selective catalytic reduction[6]	25% or more	55% to 90%	2% to 3% using urea	Potential for secondary emissions; no distribution system is currently available for urea reductant; potential for user to misfuel or fail to maintain system	Low-sulfur fuel required for systems with oxidation catalysts only	Under development for transient vehicular cycles; currently used in steady-state marine applications

NOTE: With the exception of selective catalytic reduction, these technologies require low-sulfur diesel fuel at or below 15 ppm for optimal performance.

SOURCES:
1. Johnson, 2003; certification data from the California Air Resources Board for the Johnson Matthey and Engelhard continuously regenerating, passive systems.
2. U.S. EPA certification data (EPA, 2003b).
3. DieselNet, 2000.
4. Johnson, 2003; MECA, 2003; and Majewski, 2001.
5. Johnson, 2003; Brogan, 1998.
6. Johnson, 2003; MECA, 2003; Miller, 2000.

and common rail injection systems, and the addition of advanced electronics.

High-pressure fuel injection can promote the equal diffusion of fuel and air, resulting in more complete combustion and fewer engine-out particulate emissions. HEUI systems rely on a high-pressure oil pump to control unit injectors hydraulically. HEUI is currently being used in a variety of medium-duty trucks in the United States, including Ford's "Super Duty" pickups (Ford Motor Company, 2002).

Common rail injection systems feed high-pressure fuel through a "common rail" to all of the cylinders. Particulate matter is reduced by the more complete combustion, while the formation of nitrogen oxides is limited by varying the rate of fuel injection over the duration of the injection period, ensuring the majority of fuel is burned at lower peak temperatures. Some European diesel cars and trucks currently use common rail injection, as do several heavy-duty pickups in the United States. Common rail systems may be more cost-effective in larger engines (Johnson, 2002 in Kliesch and Langer, 2003).

With electronic controls to optimize fuel injection pressure, fuel spray pattern, injection rate, and timing, advanced fuel injection systems have been demonstrated to reduce nitrogen oxide emissions by 50 percent with no significant increase in particulates (Pierpont, 1995). Systems can be optimized to reduce particulates and nitrogen oxides simultaneously, or to achieve a desired engine-out emissions profile.

Exhaust gas recirculation

Exhaust gas recirculation (EGR) returns a portion of the engine's exhaust to the combustion chamber. In the process, nitrogen oxide emissions are reduced because inert gases displace some of the oxygen that would otherwise enter the engine. The primary concerns about EGR are that particulate emissions may be increased, there is a fuel economy penalty of two to five percent, nanoparticle concentrations may be increased, and increased engine wear may effectively reduce engine lifetime.

EGR is currently being used in both heavy-duty trucks and light-duty cars and pickups in the United States in order to comply with tailpipe standards. Cooled EGR is under development to improve emissions performance.

Advanced turbochargers

Turbochargers are compressors used in many types of diesel and gasoline engines to increase air pressure. Utilizing the engine's exhaust gas and a turbine, turbochargers increase engine power by increasing the amount of air inducted into the engine, and less soot is formed due to more complete combustion. However, because turbochargers increase the temperature of the intake air, more nitrogen oxides are produced.

Advanced turbochargers (e.g., variable geometry turbochargers) rely on electronic controls to optimize combustion by controlling the air-to-fuel ratio and prevent overenrichment during stop-and-go conditions. Variable geometry turbochargers are currently used in some European cars and trucks (Diesel Technology Forum, 2001). Cooling the exhaust gas after compression can further reduce nitrogen oxide emissions and increase system durability.

Electronic superchargers have demonstrated pollution reductions of 20 to 40 percent for particulate matter and 30 to 65 percent for carbon monoxide (MECA, 2000), improving engine performance without penalizing fuel economy.

Homogenous-charge compression ignition (HCCI)

Homogenous-charge compression-ignition (HCCI) engines under development premix the

fuel to create a homogenous charge. The charge is heated during compression to allow auto-ignition. HCCI thus merges the best features of spark-ignited gasoline engines (a well-mixed charge with low particulate emissions) and compression-ignition diesel engines (no throttling losses and higher efficiency). As a result, HCCI engines should be able to achieve high efficiency and low emissions (Dibble et al., 2001).

HCCI engines should also cost less than conventional diesel engines because the fuel would be injected at lower pressures, resulting in lower materials costs. However, HCCI engines are in the early development phase, and none are commercially available at this time.

FUEL AND OIL FORMULATION CHANGES

Low-sulfur fuel

Low-sulfur fuel contains no more than 15 ppm of sulfur. Highway diesel fuel is currently held to a maximum sulfur content of 500 ppm, which will drop down to 15 ppm for most highway fuel starting in mid-2006. The EPA anticipates that reducing the amount of sulfur from 500 to 15 ppm will reduce sulfate particulates and sulfur oxide emissions by 97 percent (EPA, 1995).

More significantly for public health, many advanced emission controls require the use of low-sulfur fuel in order to function properly. Sulfur either impairs or totally compromises the performance of control technologies such as oxidation catalysts, particulate filters, lean nitrogen oxide catalysts, and exhaust gas recirculation. Low-sulfur diesel fuel is currently available in limited geographic pockets across the country, but will be widely available for use in highway vehicles starting in 2007.

Biodiesel

Biodiesel is an alternative diesel fuel commonly composed of 20 percent "pure" biodiesel (derived from biological material such as plants or animal fats) and 80 percent conventional diesel fuel. Emissions of soot, air toxics, carbon monoxide, and hydrocarbons are all reduced in biodiesel relative to conventional diesel fuels. However, nitrogen oxide emissions are increased.

According to the EPA, soybean-based pure biodiesel produces a 45 percent reduction in particulate matter and a 10 percent increase in nitrogen oxides relative to diesel (EPA, 2002c). The greater the amount of pure biodiesel in the fuel, the lower the level of toxic soot released. In addition, biodiesel has very low sulfur levels, typically below 15 ppm.

Biodiesel is gaining appeal in certain applications such as school buses, refuse haulers, and passenger vehicles. However, because it costs significantly more than conventional diesel, biodiesel is commonly blended with conventional diesel, reducing its emissions benefits.

Lubricating oils

Oils used to lubricate diesel engines can generate particulate emissions in two ways. First, the metallic portion of the oil, which cannot be burned, produces ash. Second, oil that evaporates in the crank-case and diffuses into the combustion chamber produces soot (DieselNet, 1998).Replacing metal additives with nonmetallic compounds should thus reduce the amount of ash generated, and using synthetic oils, which can be formulated to evaporate only within a narrow, high-temperature range, may also reduce particulate matter. Recent studies indicate that unburned lube oil may strongly contribute to the generation of nanoparticles, and that more research needs to be conducted in this area (Johnson, 2003).

AFTERTREATMENT TECHNOLOGIES

Aftertreatment technologies are used on the engine-out exhaust stream to reduce pollutants.

They often replace traditional muffler equipment, eliminating the need for two separate devices. While technologies to reduce soot are available today, reducing nitrogen oxides poses a significant challenge.

Reducing soot

There are two technologies for reducing particulate matter from exhaust. The first, oxidation catalysts, are currently used on diesel cars and trucks around the world, and can reduce soot by up to 50 percent. The second, particulate filters, or traps, are being offered as an option on certain European diesel vehicles. Well-functioning traps show the potential to reduce soot by 90 percent or more, and to significantly reduce the toxicity of per-mile emissions.

1. ***Oxidation catalysts***. Oxidation catalysts reduce the amount of particulate matter by transforming carbon particles into carbon dioxide. As exhaust passes through an oxidation catalyst, the precious metal catalyst oxidizes the carbon monoxide, gaseous hydrocarbons, and liquid hydrocarbons adsorbed onto carbon particles. According to EPA tests, oxidation catalysts can reduce particulates by 20 to 50 percent on older engines (EPA, 2001).

A key factor influencing their effectiveness is the level of sulfur in the diesel fuel. Because oxidation catalysts also oxidize sulfur dioxide, forming particulate sulfate emissions, they are most effective at reducing particulate emissions when the sulfur content of the diesel fuel is low. Some 35 million diesel passenger cars currently rely on oxidation catalysts to reduce particulate emissions (MECA, 2003).

2. ***Diesel particulate filters***. Diesel particulate filters, also known as PM traps, capture particulates in the engine's exhaust stream. Early evidence indicates that well-functioning filters can reduce particulate levels more than 90 percent (LeTavec, 2000; CARB, 2002; Johnson, 2003; Ecotraffic, 2002). In addition to reducing the mass of particulate emissions, filters also appear to significantly reduce toxicity.

Diesel particulate filters will trap both combustible particles such as carbon soot and noncombustible materials, including the metals resulting from engine wear and the ash from lubricating oils. To clean the filters, the combustible particles must be oxidized (burned) through either passive or active ignition.

Passive systems, which are being used on some new highway school and transit buses, use a catalyst to lower the oxidation temperature of the exhaust stream. Active systems use sparks or a heating device such as a microwave to heat the particles to the temperature needed for ignition (around 500º Celsius). Since they require additional energy to fuel the heating device, active systems carry a small fuel economy penalty. They are also slightly more expensive than passive systems.

The performance of passive systems can be impaired by sulfur in the exhaust. Sulfur oxides compete for the catalyst sites required to convert nitrogen oxide into nitrogen dioxide, increasing the temperature required for successful regeneration and making regeneration less effective. In addition, sulfur can be oxidized on the filter itself, clogging the device.

Unfortunately, the first generation of passive traps may create an unintended pollution problem: more smog (urban ozone). While these traps do not affect the total amount of nitrogen oxides released from the tailpipe, they appear to increase the relative share of nitrogen dioxide, which is more reactive in the formation of ozone than other oxides of nitrogen (McNerny, 2002).

Active and passive particulate filters are being offered as options on some European diesel

cars.[33] Two passive traps have been certified for use on heavy-duty trucks and buses in the United States, but none have been certified for use on passenger cars or trucks.[34] At this point, diesel particulate filters are no longer in the development phase, but engineers are optimizing their performance and trying to integrate them with nitrogen oxide controls.

Key issues are consistent and effective filter regeneration, controlling engine backpressures, managing ash on the filter, and ensuring proper trap maintenance. In addition, more research needs to be conducted on the generation of nanoparticles by trap operation, particularly during the regeneration process (Johnson, 2003).

Reducing nitrogen oxides

Controlling nitrogen oxide emissions is proving more technically challenging than controlling soot. Only one technology, the lean nitrogen oxide catalyst, has been verified in the United States. The two technologies with the greatest potential to reduce nitrogen oxides—adsorbers and selective catalytic reduction—are still in the development phase.

Nitrogen oxide adsorbers,[35] also called NOx traps, have not proved durable over the exhaust temperature profile typical of diesel engines (Duo and Bailey, 1998; Johnson, 2003). Selective catalytic reduction,[36] which has been used for years in stationary engines and some marine applications, also poses significant technical challenges. Manufacturers must modify the technology from the steady-state conditions of stationary sources to the transient cycles of vehicles, which also have lower exhaust temperatures. In addition, selective catalytic reduction is more complex, larger in size, and more costly than other catalyst systems.

1. ***Lean nitrogen oxide catalysts***. Lean nitrogen oxide catalysts reduce nitrogen oxide emissions in the presence of the oxygen-rich exhaust stream typical of diesel engines, and can reduce these emissions by 30 percent. This technology typically uses hydrocarbons to convert nitrogen oxides into nitrogen gas, carbon dioxide, and water. Because hydrocarbons are not concentrated sufficiently in the exhaust stream, they (typically diesel fuel) are injected directly into the exhaust, providing the environment necessary for nitrogen oxide reduction. This strategy does, however, carry a fuel economy penalty.

In 2003, the California Air Resources Board verified the first combination lean nitrogen oxide catalyst and particulate filter for retrofitting certain

33 In 2000, Peugeot Citroen was the first automaker to offer an active diesel particulate filter system as an option for its cars. Other automakers including Ford, General Motors, Mercedes, Toyota, and Volkswagen have followed suit, offering diesel particulate filters as either options or standard equipment. In 2003, the first catalyzed passive trap was marketed on one of Renault's luxury cars.

34 The two traps certified for use with heavy-duty trucks and buses are the Johnson-Matthey Continuously Regenerating Trap (CRT) and the Engelhard catalytic soot filter (called the DPX). Both devices are installed in place of the existing muffler system, without any engine modifications, and both use a catalyst to lower the temperatures required to ignite and oxidize particles from the filter. The CRT is a two-stage system. As exhaust gases flow through the platinum catalyst, nitric oxide and other nitrogen oxides are converted into nitrogen dioxide. The catalyst also converts carbon monoxide and hydrocarbons into carbon dioxide and water. The exhaust gases then pass through a filter that traps the soot particles. Through a chemical reaction between the soot and nitrogen dioxide, the combustion temperature is lowered to 250° Celsius, well within the normal temperature range of diesel exhaust. Thus, the trap continuously self-regenerates during the vehicle's normal operation. The DPX is a single-stage system, using a ceramic wall-flow filter coated in platinum.

35 Nitrogen oxide adsorbers convert nitrogen oxides to nitrogen gas and oxygen in a two-step process. First, the exhaust gas passes through a catalyst, which chemically "traps" and stores the nitrogen oxides. Once the catalyst's active sites are "filled" hydrocarbons (usually in the form of diesel fuel) are injected directly into the exhaust gas. The hydrocarbons react with the nitrogen oxides to create nitrogen gas (N_2), oxygen (O_2), and water (H_2O). The injection of hydrocarbons into the exhaust gas exacts a fuel economy penalty; projected between two and five percent.

36 Selective catalytic reduction (SCR) converts nitrogen oxides to gaseous nitrogen and water vapor through a chemical reaction with ammonia. Since pure ammonia is hazardous, solutions of urea (ammonia bonded to carbon monoxide) may be used instead. The ammonia or urea is injected into the exhaust upstream of the catalyst. When the gases pass through a catalyst coated with a ceramic or metallic substrate, 75 to 90 percent of the nitrogen oxides, 50 to 90 percent of the hydrocarbons, and 30 to 50 percent of the particulates are removed (MECA, 2000).

heavy-duty highway diesel engines built in 1994 or later. The Longview system, designed by Cleaire Advanced Emission Controls as a muffler replacement unit, is the first retrofit equipment available for nitrogen oxide control and has been verified to reduce nitrogen oxides by 25 percent and particulates by 85 percent, with a fuel economy penalty between three and seven percent depending on the application (CARB, 2003c). As yet, no lean nitrogen oxide catalysts or particulate filters are approved for use on light-duty cars.

2. ***Adsorbers***. By trapping nitrogen oxides in a catalyst washcoat during oxygen-rich driving conditions and releasing the nitrogen later in lean conditions, nitrogen oxide adsorbers, or traps, can potentially reduce nitrogen oxides 80 percent or more. Before this technology can be marketed, however, significant technical hurdles must be overcome. Current systems have not proved durable over the exhaust temperature profile typical of diesel engines (Johnson, 2003; Duo and Bailey, 1998) or able to tolerate sulfur contamination.

Nitrogen oxide adsorbers require the periodic injection of a reducing agent such as hydrocarbons in order to regenerate the catalyst washcoat. This can be accomplished by either injecting fuel into the engine on the exhaust stroke (in single-path systems) or by switching the exhaust (in dual-path systems) and injecting fuel to regenerate one catalyst bed while the parallel catalyst bed is adsorbing nitrogen oxides. Single-path systems require less capital, but exact a fuel economy penalty. Dual-path systems have a lower fuel economy penalty since less fuel is necessary in the closed catalyst bed, but the capital costs are higher. The complex exhaust configurations and valves necessary for exhaust flow management and catalyst regeneration make adsorbers an expensive option.

Further engineering considerations include the fact that nitrogen oxide adsorbers must be able to manage higher exhaust temperatures both in the engine (at the exhaust manifold) and within the exhaust components and catalysts. Adsorbers also require a good deal of space, with volumes ranging from as low as 1.5 times the engine displacement for a single-path system to five times for a dual-path system.

This technology has the potential to reduce nitrogen oxides by 90 percent to meet the Tier 2 requirements. Adsorbers have been successfully demonstrated in commercial use with lean-burning gasoline engines, but they have not been tested in diesel engines, which raises concerns about fuel contaminants that might reduce the catalyst's effectiveness. Unlike selective catalytic reduction (see below), nitrogen oxide adsorbers are self-contained and do not require the continual replenishment of a reagent. Opportunities to defeat this type of system are more limited than with selective catalytic reduction.

3. ***Selective catalytic reduction***. Selective catalytic reduction (SCR) reduces nitrogen oxide emissions by using a chemical reagent (typically ammonia or urea) to convert nitrogen oxides into gaseous nitrogen and water vapor. This process can theoretically reduce nitrogen oxides more than 90 percent, and also control hydrocarbon and particulate emissions. However, SCR is sensitive to the timing and amount of the reagent, variations in exhaust temperature, exhaust gas flow, and concentration of nitrogen oxides in the exhaust.

Toxic pollution in the form of ammonium nitrate particulates and ammonia can result if the reagent is injected at the wrong time or in the wrong amount (DieselNet, 2000b). If not enough urea is injected, for example, the catalyst stops working and nitrogen oxides are no longer reduced. If too much urea is injected, it passes through the catalyst (termed "slip") and is emitted into the atmosphere as ammonia. Increasing the catalyst volume can alleviate this issue, but at the cost of money and space. The catalyst may also be

susceptible to poisoning from diesel exhaust constituents such as lube oil additives.

Because SCR requires sufficient exhaust temperatures to operate correctly, cold-start operation and excess idle are problematic. The catalyst also requires a larger amount of space than other emission control technologies (potentially two to three times the engine displacement), but it is relatively inexpensive and the materials are widely available.

SCR has been used for years on stationary engines and some marine applications, but its use on vehicles is still in the development phase. The technology has drawn significant interest because it may offer the highest level of nitrogen oxide control, and is being applied in demonstration vehicles such as the Ford Focus and some of the larger Class 8 heavy-duty trucks. However, shifting the technology from the steady-state conditions of stationary sources to the transient cycles of heavy diesel equipment poses significant challenges. SCR is more complex relative to other catalyst systems, larger in size, and more costly.

Europeans consider SCR one of the front-running technologies for meeting future emissions standards, but it is unclear whether the technology will pass verification tests in the United States. Concerns about secondary pollution from the accidental release of urea or ammonia, as well as the durability and real-world performance of SCR, continue to plague its development.

If SCR proves to be the premier nitrogen oxide control strategy, significant infrastructure changes would be required. Filling stations would need to offer dual-fuel capacity, providing both low-sulfur diesel fuel and the urea (or ammonia) necessary for the selective catalytic reduction to function. Currently, there is neither an incentive for the vehicle operator to invest in the additional cost of the urea, nor an established distribution network available.

Appendix B
Test Results by Technology Package

Chapter Two presents a summary of fleetwide results for 10 technology packages (five for gasoline and five for diesel) applied to each of five car and truck classes. A more detailed description of these technology packages, cost and performance assumptions, and the individual results for each package and vehicle class follows.

BASELINE DIESEL PACKAGE

The "baseline" diesel package incorporates a turbo direct-injection (TDI) diesel engine similar to Volkswagen's 90 hp, 1.9 liter TDI currently available in the United States for the New Beetle, Jetta, and Golf models. This engine incorporates a variable geometry turbocharger, EGR, optimized higher-pressure injectors, and improved engine calibration to achieve improved fuel economy and relatively low emissions for an uncontrolled diesel engine.

The 1.9 liter MY 2003 Jetta, Golf, and New Beetle diesel cars with automatic transmissions achieve a roughly 46 percent increase in fuel economy (mpg diesel versus mpg gasoline) compared with the most similar gasoline versions (featuring a 115 hp, 2.0 liter gasoline engine).[37] The manual transmission versions achieve more than a 60 percent increase in fuel economy. However, the added power in gasoline versions gives them a two- to three-second faster 0 to 60 mph acceleration time than the diesel vehicles.[38] If similar 0 to 60 mph acceleration performance were achieved, a larger diesel engine would be required and the fuel economy increase would be reduced.

Other than appropriately sizing the engine to match the 0 to 60 mph acceleration times for each vehicle modeled and the inclusion of the emission control technology needed to meet Tier 2 Bin 5 emission levels, no other modifications are made in comparison with the baseline MY 2000 gasoline vehicles. This engine technology could be widely implemented across the U.S. passenger fleet within the next five to seven years if automakers are successful in developing the necessary emission control technologies. This latter point is very important, as there is still significant concern that diesel will fall short of meeting the Bin 5 standard and will only achieve Bin 8 (see Chapter Four).

The incremental retail cost for the baseline diesel engine is adapted from Plotkin et al., 2002, where the cost of a four-cylinder TDI engine plus emission controls was estimated to be $1,600 and the cost of a six-cylinder TDI engine plus emission controls was estimated to be $2,200. Given these values, we assumed another increase of $600 for an eight-cylinder TDI engine, resulting in an incremental retail cost increase of $2,800.

Plotkin et al. also note that manufacturer estimates indicated a range of $400 to $600 as reasonable "targets" for the cost of emission controls that

37 MY 2004 fuel economy benefits for the Volkswagen vehicles dropped to the mid- to low-40 percent range for the automatic transmission versions and about 50 percent for the manual transmission versions. This drop is likely due to the use of a more powerful engine (100 hp instead of 90) to achieve more comparable performance.

38 Acceleration data for MY 2003 vehicles were obtained from Volkswagen's website (*www.vw.com*), but that information is no longer available and the MY 2004 acceleration data for diesel vehicles were not yet posted as of the writing of this report. Similar information on the 2003 Jetta with manual transmission was found at the MSN auto website (Heraud, 2003).

could meet Tier 2 Bin 5 standards later in this decade. We assume that these costs are a range for four-cylinder engines and use the midpoint value of $500. We then assume that these costs increase by $125 for six-cylinder engines and another $125 for eight-cylinder engines, and subtract these costs from the values in Plotkin et al., 2002 to determine the baseline diesel engine price increase.[39]

In Table B-1, these costs have been broken out to demonstrate the contribution that emission control equipment and the diesel engine have on the vehicle's price. This table also includes estimates for the cost of reaching Bin 5 with gasoline vehicles—based on retail cost estimates from the EPA's Tier 2 Regulatory Impact Analysis (EPA, 1999)—and the resulting net cost for diesel engine packages.

The size of the diesel engines for each vehicle was chosen so that its 0 to 60 mph acceleration performance would be matched against the baseline gasoline vehicles. However, because diesel engines provide more torque at low speeds than gasoline vehicles and less torque at high speeds, the baseline diesel vehicle offers better performance around town (acceleration from 0 to 30 mph), but worse performance on the highway (acceleration from 30 to 60 mph). Because of this, a perfect apples-to-apples comparison with gasoline vehicles is not possible, but this strategy was chosen as the best compromise since some consumers may place a different value on certain performance characteristics.

The modeled fuel economy of the diesel package is reduced by five percent to account for the fuel economy penalty associated with achieving Tier 2 Bin 5 emission levels. This penalty is an estimate combining the fuel penalties associated with nitrogen oxide control that engine manufacturers currently estimate between four and five percent (Plotkin et al., 2002) and the fuel loss needed to provide active regeneration, which may be required to clean out particulate traps.[40]

Table B-1 **Retail Price Increase for Baseline Diesel Engine Package**

Engine Size	Diesel Engine	Diesel Emission Controls	Gasoline Emission Controls	Net Price Increase
4-Cylinder	$1,100	$500	$50	$1,550
6-Cylinder	$1,575	$625	$100	$2,100
8-Cylinder	$2,050	$750	$200	$2,600

MODERATE DIESEL PACKAGE

The "moderate" diesel package incorporates the same engine and emission controls as the baseline diesel package, and thus draws on the same package costs listed in Table B-1. In addition, the moderate package includes a modest transmission technology improvement and modest vehicle load reduction technologies, costing consumers about $270 extra for the average vehicle.

All of the technologies listed in Table B-2, with the exception of the emission controls, are already in mass production within the United States, though they are not all widely used throughout the passenger vehicle fleet. As a result, this package could be widely implemented within the next five to seven years assuming success with emission controls.

ADVANCED DIESEL PACKAGE

The "advanced" diesel package incorporates several significant changes from the moderate package. As outlined in Table B-3, this configura-

39 We assume that 50 percent of the emission control costs ($250) are fixed and that the other 50 percent are proportionate to the number of cylinders. Thus, the price increase grows by $125 when the engine is expanded by two cylinders.

40 Johnston, 2003 indicates that the penalty for nitrogen oxide control currently ranges from two to six percent for heavy-duty vehicles.

Table B-2 **Features of Moderate Diesel Technology Package**

Today's TDI diesel engine (in the United States)
Continuously variable transmission or 5-speed automatic transmission with optimized shift schedule
Vehicle load reduction • 10% reduction in aerodynamic drag • 20% reduction in rolling resistance • 0% mass reduction for small cars, 10% for family cars, and 20% for light trucks using high-strength steel
Tier 2 Bin 5 emission controls

Table B-3 **Features of Advanced Diesel Technology Package**

Advanced TDI diesel engine
Advanced continuously variable transmission or 6-speed automatic transmission with optimized shift schedule
42-volt integrated starter-generator with idle off and torque smoothing
Vehicle load reduction • 10% reduction in aerodynamic drag • 20% reduction in rolling resistance • 10% mass reduction for small cars, 20% for family cars, and 30% for light trucks using high-strength steel • Efficient accessories
Tier 2 Bin 5 emission controls

Table B-4 **Retail Price Increase for Advanced Diesel Engine Package**

Engine Size	Diesel Engine	Diesel Emission Controls	Gasoline Emission Controls	Net Price Increase
4-Cylinder	$1,610	$500	$50	$2,060
6-Cylinder	$2,150	$625	$100	$2,675
8-Cylinder	$2,690	$750	$200	$3,240

tion incorporates improvements that could be achieved throughout the fleet within the next 10 to 15 years.

The advanced TDI diesel engine is derived from the potential improvements in diesel engines put forth by Weiss et al. in two reports, *On the Road in 2020: A Life-Cycle Analysis of New Automobile Technologies* (2000) and *Comparative Assessment of Fuel Cell Cars* (2003). This engine represents an aggressive improvement in diesel technology: a 15 percent improvement in peak efficiency and a 20 percent improvement in power density compared with the baseline TDI engine. Again, emission controls are added to reach the Tier 2 Bin 5 standard.

The price increase for the four-cylinder version of this advanced diesel engine is also taken from Weiss et al., 2000.[41] The emission control costs are assumed to be the same as those used in the base-line case, though in reality, emission control may be more difficult if higher compression ratios and therefore higher temperatures are used to achieve the improved diesel efficiency. These costs and the net price increase are shown in Table B-4.

In addition, the advanced package includes a 42-volt integrated starter-generator (ISG) system. This is a beefed-up alternator that allows the engine to be shut off rather than left idling at stoplights and in heavy stop-and-go traffic. Along with the move to a 42-volt system comes efficiency improvements in vehicle accessories, such as the inclusion of electric power steering and braking. The advanced package also incorporates a more significant transmission technology improvement along with the same aerodynamic and rolling resistance reductions from the moderate package.

Finally, this advanced package goes a step further by more aggressively using high-strength steel and aluminum throughout the vehicle fleet. The most significant weight reductions are concentrated in the heaviest vehicles. The result is a fleet

41 The price increase in Weiss et al., 2000 for a four-cylinder advanced TDI diesel engine, $1,500 in 1997 dollars, has been increased by 7.3 percent to account for inflation from 1997 through 2000. The price increase for the six- and eight-cylinder engines is assumed by the authors to be $500 and $1,000 (in 1997 dollars), in line with that used for the baseline diesel engine.

of vehicles that are safer for their passengers through the use of good design practices and high-strength materials, and safer for others on the road due to the reduced aggressivity associated with their lower weight. The safe and effective use of high-strength steel and aluminum has been demonstrated by the steel, aluminum, and auto industry through several design studies and vehicle demonstration projects (AISI, 1997; AISI, 2001; ULSAB, 2001a; ULSAB, 2001b; Ford, 2001).

The total added cost to consumers for the ISG, transmission, high-strength materials, and other load reduction technologies is about $1,245 for the average advanced vehicle package.

ADVANCED MILD HYBRID DIESEL PACKAGE (ESTIMATED)

The advanced mild hybrid diesel package is designed as an upgrade from the advanced diesel package. All of the same fuel economy and emission control technologies and associated costs are used, with the exception of the integrated starter-generator, which is removed and replaced with a more advanced electric motor and nickel-metal hydride battery pack. The electric motor and battery pack offer the following opportunities: reducing the size of the engine by providing a power boost when needed (engine downsizing with power assist); recapturing energy typically lost when stopping the vehicle through regenerative braking; and even more aggressive idle-off capability than the ISG. The average added consumer cost for the mild hybrid package, including the discounted cost for future battery replacements, but excluding the engine and emission control costs, is $2,370.[42]

This hybrid configuration uses a parallel hybrid drivetrain and is intended to represent the hybrid technology used in the Honda Civic Hybrid. As noted previously, this hybrid configuration is assumed to achieve an optimistic average fuel economy improvement of 19 percent over the conventional advanced diesel package. See *A New Road: The Technology and Potential of Hybrid Vehicles* (Friedman, 2003) for more details on mild hybrids and the performance and costs of the gasoline version of this package.

Since this hybrid diesel package was not simulated, its acceleration cannot be matched against the baseline vehicles. However, since the gasoline version that this is based on was designed to exceed the 0 to 60 mph acceleration performance of the baseline vehicle, the diesel hybrid should also provide superior performance.

As with the other diesel vehicles, a five percent fuel economy penalty is applied in association with meeting the Bin 5 emissions standards. It is possible that diesel hybrids may be able to achieve lower fuel economy penalties when meeting emissions standards by incorporating new emission control systems that take advantage of onboard electrical power, but such systems have yet to be developed. This might cancel out the optimistic fuel economy assumption, but more research is needed to provide a more detailed result.

ADVANCED FULL HYBRID DIESEL PACKAGE (ESTIMATED)

The advanced full hybrid diesel package is designed as an upgrade from the advanced mild hybrid diesel package. All of the same fuel economy and emission control technologies and costs are used; however, a larger motor and battery pack and a smaller engine are incorporated to further improve fuel economy. In addition to the hybrid capabilities in the mild hybrid, the larger motor and battery pack enable the full hybrid diesel

42 This average retail cost increase includes the hybrid system, the conventional technologies from the advanced case, and a credit for dropping the ISG.

vehicle to drive using only electric power at lower speeds. The larger motor and battery pack drive the added consumer cost up by about $3,475, excluding engine and emission control costs.

This hybrid configuration uses a parallel hybrid drivetrain and is intended to represent fuel economy improvements similar to those seen in the 2004 Toyota Prius. As noted previously, this hybrid configuration is assumed to achieve an optimistic average fuel economy improvement of 41 percent over the conventional advanced diesel package. See Friedman, 2003 for more details on full hybrids and the performance and costs of the gasoline version of this package. As with the mild hybrid, the 0 to 60 mph performance, though not simulated, is expected to be superior to the baseline vehicle, and the same fuel economy penalty for emission control is applied.

GASOLINE PACKAGES

The five gasoline technology packages we compared with diesel vehicles are nearly the same as those used in the study of conventional gasoline and gasoline hybrid-electric vehicle technology by Friedman (2003), and that report should be consulted for further details not included in this report.[43] The additional cost associated with the emission controls needed for the gasoline vehicles to meet Tier 2 Bin 5 standards is included in the baseline gasoline vehicles.[44] The fuel economy and performance results are presented in more detail in the following tables.

43 A slightly different fleet mix for trucks was used in this report due to updated information for the fleet mix in 2000.

44 Other than the baseline vehicle, the gasoline cases include some engine downsizing, thereby allowing a reduction in the cost of the emission control equipment. The net cost for emission controls appears negative for some gasoline cases. This allows the incremental costs to represent only the costs required to improve fuel economy for both gasoline and diesel vehicles, where the net difference between emission controls for diesel and gasoline vehicles represents a cost necessary for the vehicle to be included as a fuel economy improvement package.

Table B-5 **Impact of Improved Gasoline, Diesel, Conventional, and Hybrid Technology on a Compact Car (Chevrolet Cavalier)**

Vehicle Technology	Baseline	Moderate	Advanced	Advanced	Advanced
Vehicle Type	**Conventional**	**Conventional**	**Conventional**	**Mild Hybrid**	**Full Hybrid**
Gasoline					
CAFE-rated fuel economy[a] (mpg)	30.8	39.2	48.4	58.7	67.3
Gasoline-equivalent CAFE fuel economy[b] (mpgge)	30.8	39.2	48.4	58.7	67.3
Real-world fuel economy[c] (mpgge)	25.2	32.2	39.7	48.1	55.2
Fuel economy improvement from baseline		28%	57%	91%	119%
Incremental retail cost increase[d]		$444	$1,125	$2,746	$3,744
Lifetime fuel cost savings[e]		$1,449	$2,481	$3,277	$3,765
Lifetime net savings[f]		$1,004	$1,356	$531	$21
Lifetime global warming pollution savings[g] (tons)		16.4	28.1	37.1	42.6
Cost-effectiveness (net cost per ton of CO_2-equivalent emissions)		-61.3	-48.3	-14.3	-0.5
Lifetime oil savings[h] (barrels)		32.7	55.9	73.9	84.9
Cost-effectiveness (net cost per barrel of oil)		-30.8	-24.2	-7.2	-0.2
Diesel					
CAFE-rated fuel economy[a] (mpg)	41.5	46.4	60.7	73.6	84.4
Gasoline-equivalent CAFE fuel economy[b] (mpgge)	36.6	40.9	53.5	64.9	74.4
Real-world fuel economy[c] (mpgge)	30.0	33.5	43.9	53.2	61.0
Fuel economy improvement from baseline	19%	33%	74%	111%	142%
Incremental retail cost increase[d]	$1,550	$1,724	$2,734	$4,356	$5,354
Lifetime fuel cost savings[e]	$1,748	$2,286	$3,404	$4,054	$4,450
Lifetime net savings[f]	$198	$562	$670	-$302	-$903
Lifetime global warming pollution savings[g] (tons)	9.0	16.2	31.0	39.6	44.9
Cost-effectiveness (net cost per ton of CO_2-equivalent emissions)	-21.9	-34.7	-21.6	7.6	20.1
Lifetime oil savings[h] (barrels)	8.9	24.0	55.4	73.7	84.8
Cost-effectiveness (net cost per barrel of oil)	-22.2	-23.4	-12.1	4.1	10.7

NOTES:

a. Composite city/highway fuel economy over the EPA test cycle used in determining Corporate Average Fuel Economy (CAFE) compliance.

b. CAFE test results adjusted for the energy content in the fuel relative to gasoline.

c. Gasoline-equivalent CAFE results adjusted by 18% to better represent on-road performance.

d. Increase in manufacturer's suggested retail price. Excludes tax, title, and destination charges. Includes net costs to meet Tier 2, Bin 5 standards compared with baseline vehicle that meets the same emission levels.

e. Lifetime fuel cost savings based on the difference between the baseline gasoline vehicle and the cases shown here. Includes the following assumptions: average gasoline price of $1.40 per gallon; average diesel price of $1.40 per gallon; 15-year average vehicle lifetime; annual mileage of 15,600 in the first year, declining by 4.5% per year, and modified by a 10% rebound effect based on the per-mile cost of driving; and real discount rate of 5% (equivalent to an 8% new car loan).

f. Lifetime net savings based on the difference between the increase in MSRP and the lifetime fuel cost savings.

g. Lifetime global warming pollution savings presented as carbon dioxide-equivalent emissions from the vehicle tailpipe and upstream fuel manufacturing and delivery. Emissions from vehicle manufacturing, refrigerant leaks, and other sources are not included. Emissions are based on the same vehicle lifetime and mileage estimates used to calculate lifetime fuel cost.

h. Lifetime oil requirement presented as the amount of oil required to make the gasoline or diesel fuel used during the vehicle's lifetime, incorporating the same life and mileage estimates used to calculate lifetime fuel cost.

Table B-6 **Impact of Improved Gasoline, Diesel, Conventional, and Hybrid Technology on a Family Car (Ford Taurus)**

Vehicle Technology	Baseline	Moderate	Advanced	Advanced	Advanced
Vehicle Type	**Conventional**	**Conventional**	**Conventional**	**Mild Hybrid**	**Full Hybrid**
Gasoline					
CAFE-rated fuel economy[a] (mpg)	26.2	36.2	45.8	54.4	66.3
Gasoline-equivalent CAFE fuel economy[b] (mpgge)	26.2	36.2	45.8	54.4	66.3
Real-world fuel economy[c] (mpgge)	21.5	29.7	37.5	44.6	54.4
Fuel economy improvement from baseline		38%	75%	108%	153%
Incremental retail cost increase[d]		$536	$1,242	$2,783	$4,157
Lifetime fuel cost savings[e]		$2,191	$3,436	$4,207	$4,953
Lifetime net savings[f]		$1,655	$2,194	$1,424	$797
Lifetime global warming pollution savings[g] (tons)		24.8	38.9	47.6	56.1
Cost-effectiveness (net cost per ton of CO_2-equivalent emissions)		-66.8	-56.4	-29.9	-14.2
Lifetime oil savings[h] (barrels)		49.4	77.5	94.9	111.7
Cost-effectiveness (net cost per barrel of oil)		-33.5	-28.3	-15.0	-7.1
Diesel					
CAFE-rated fuel economy[a] (mpg)	37.6	43.6	57.4	68.3	83.2
Gasoline-equivalent CAFE fuel economy[b] (mpgge)	33.1	38.5	50.6	60.2	73.3
Real-world fuel economy[c] (mpgge)	27.1	31.5	41.5	49.3	60.1
Fuel economy improvement from baseline	26%	47%	93%	130%	180%
Incremental retail cost increase[d]	$2,100	$2,276	$2,852	$4,393	$5,766
Lifetime fuel cost savings[e]	$2,401	$3,203	$4,426	$5,054	$5,659
Lifetime net savings[f]	$301	$927	$1,574	$661	-$108
Lifetime global warming pollution savings[g] (tons)	15.3	25.9	42.1	50.4	58.5
Cost-effectiveness (net cost per ton of CO_2-equivalent emissions)	-19.7	-35.8	-37.4	-13.1	1.8
Lifetime oil savings[h] (barrels)	20.2	42.8	77.1	94.7	111.7
Cost-effectiveness (net cost per barrel of oil)	-14.9	-21.7	-20.4	-7.0	1.0

NOTES:

a. Composite city/highway fuel economy over the EPA test cycle used in determining Corporate Average Fuel Economy (CAFE) compliance.

b. CAFE test results adjusted for the energy content in the fuel relative to gasoline.

c. Gasoline-equivalent CAFE results adjusted by 18% to better represent on-road performance.

d. Increase in manufacturer's suggested retail price. Excludes tax, title, and destination charges. Includes net costs to meet Tier 2, Bin 5 standards compared with baseline vehicle that meets the same emission levels.

e. Lifetime fuel cost savings based on the difference between the baseline gasoline vehicle and the cases shown here. Includes the following assumptions: average gasoline price of $1.40 per gallon; average diesel price of $1.40 per gallon; 15-year average vehicle lifetime; annual mileage of 15,600 in the first year, declining by 4.5% per year, and modified by a 10% rebound effect based on the per-mile cost of driving; and real discount rate of 5% (equivalent to an 8% new car loan).

f. Lifetime net savings based on the difference between the increase in MSRP and the lifetime fuel cost savings.

g. Lifetime global warming pollution savings presented as carbon dioxide-equivalent emissions from the vehicle tailpipe and upstream fuel manufacturing and delivery. Emissions from vehicle manufacturing, refrigerant leaks, and other sources are not included. Emissions are based on the same vehicle lifetime and mileage estimates used to calculate lifetime fuel cost.

h. Lifetime oil requirement presented as the amount of oil required to make the gasoline or diesel fuel used during the vehicle's lifetime, incorporating the same life and mileage estimates used to calculate lifetime fuel cost.

Table B-7 **Impact of Improved Gasoline, Diesel, Conventional, and Hybrid Technology on a Full-Size Pickup (Chevrolet Silverado 1500)**

Vehicle Technology	Baseline	Moderate	Advanced	Advanced	Advanced
Vehicle Type	**Conventional**	**Conventional**	**Conventional**	**Mild Hybrid**	**Full Hybrid**
Gasoline					
CAFE-rated fuel economy[a] (mpg)	20.3	26.5	33.7	40.2	48.8
Gasoline-equivalent CAFE fuel economy[b] (mpgge)	20.3	26.5	33.7	40.2	48.8
Real-world fuel economy[c] (mpgge)	16.6	21.8	27.7	33.0	40.0
Fuel economy improvement from baseline		31%	66%	98%	140%
Incremental retail cost increase[d]		$665	$2,191	$3,739	$5,448
Lifetime fuel cost savings[e]		$2,391	$4,120	$5,173	$6,160
Lifetime net savings[f]		$1,726	$1,930	$1,434	$712
Lifetime global warming pollution savings[g] (tons)		27.1	46.6	58.5	69.7
Cost-effectiveness (net cost per ton of CO_2-equivalent emissions)		-63.8	-41.4	-24.5	-10.2
Lifetime oil savings[h] (barrels)		53.9	92.9	116.6	138.9
Cost-effectiveness (net cost per barrel of oil)		-32.0	-20.8	-12.3	-5.1
Diesel					
CAFE-rated fuel economy[a] (mpg)	28.0	34.0	45.0	53.6	65.1
Gasoline-equivalent CAFE fuel economy[b] (mpgge)	24.7	30.0	39.7	47.2	57.3
Real-world fuel economy[c] (mpgge)	20.2	24.6	32.5	38.7	47.0
Fuel economy improvement from baseline	22%	48%	95%	133%	183%
Incremental retail cost increase[d]	$2,600	$2,880	$4,306	$5,854	$7,563
Lifetime fuel cost savings[e]	$2,802	$4,178	$5,768	$6,579	$7,336
Lifetime net savings[f]	$202	$1,298	$1,462	$725	-$227
Lifetime global warming pollution savings[g] (tons)	15.8	34.0	55.1	65.8	75.9
Cost-effectiveness (net cost per ton of CO_2-equivalent emissions)	-12.8	-38.2	-26.5	-11.0	3.0
Lifetime oil savings[h] (barrels)	17.8	56.4	101.1	123.8	145.1
Cost-effectiveness (net cost per barrel of oil)	-11.3	-23.0	-14.5	-5.9	1.6

NOTES:

a. Composite city/highway fuel economy over the EPA test cycle used in determining Corporate Average Fuel Economy (CAFE) compliance.

b. CAFE test results adjusted for the energy content in the fuel relative to gasoline.

c. Gasoline-equivalent CAFE results adjusted by 18% to better represent on-road performance.

d. Increase in manufacturer's suggested retail price. Excludes tax, title, and destination charges. Includes net costs to meet Tier 2, Bin 5 standards compared with baseline vehicle that meets the same emission levels.

e. Lifetime fuel cost savings based on the difference between the baseline gasoline vehicle and the cases shown here. Includes the following assumptions: average gasoline price of $1.40 per gallon; average diesel price of $1.40 per gallon; 15-year average vehicle lifetime; annual mileage of 15,600 in the first year, declining by 4.5% per year, and modified by a 10% rebound effect based on the per-mile cost of driving; and real discount rate of 5% (equivalent to an 8% new car loan).

f. Lifetime net savings based on the difference between the increase in MSRP and the lifetime fuel cost savings.

g. Lifetime global warming pollution savings presented as carbon dioxide-equivalent emissions from the vehicle tailpipe and upstream fuel manufacturing and delivery. Emissions from vehicle manufacturing, refrigerant leaks, and other sources are not included. Emissions are based on the same vehicle lifetime and mileage estimates used to calculate lifetime fuel cost.

h. Lifetime oil requirement presented as the amount of oil required to make the gasoline or diesel fuel used during the vehicle's lifetime, incorporating the same life and mileage estimates used to calculate lifetime fuel cost.

Table B-8 **Impact of Improved Gasoline, Diesel, Conventional, and Hybrid Technology on a Minivan (Dodge Grand Caravan)**

Vehicle Technology	Baseline	Moderate	Advanced	Advanced	Advanced
Vehicle Type	**Conventional**	**Conventional**	**Conventional**	**Mild Hybrid**	**Full Hybrid**
Gasoline					
CAFE-rated fuel economy[a] (mpg)	22.4	31.7	41.3	49.1	57.6
Gasoline-equivalent CAFE fuel economy[b] (mpgge)	22.4	31.7	41.3	49.1	57.6
Real-world fuel economy[c] (mpgge)	18.3	26.0	33.9	40.3	47.2
Fuel economy improvement from baseline		42%	85%	120%	158%
Incremental retail cost increase[d]		$750	$2,084	$2,975	$4,310
Lifetime fuel cost savings[e]		$2,737	$4,336	$5,192	$5,874
Lifetime net savings[f]		$1,987	$2,253	$2,218	$1,565
Lifetime global warming pollution savings[g] (tons)		31.0	49.1	58.8	66.5
Cost-effectiveness (net cost per ton of CO_2-equivalent emissions)		-64.2	-45.9	-37.7	-23.5
Lifetime oil savings[h] (barrels)		61.7	97.8	117.1	132.4
Cost-effectiveness (net cost per barrel of oil)		-32.2	-23.0	-18.9	-11.8
Diesel					
CAFE-rated fuel economy[a] (mpg)	31.2	36.8	51.2	60.9	71.4
Gasoline-equivalent CAFE fuel economy[b] (mpgge)	27.5	32.4	45.1	53.6	62.9
Real-world fuel economy[c] (mpgge)	22.5	26.6	37.0	44.0	51.6
Fuel economy improvement from baseline	23%	45%	102%	140%	181%
Incremental retail cost increase[d]	$2,100	$2,490	$3,693	$4,584	$5,919
Lifetime fuel cost savings[e]	$2,624	$3,677	$5,383	$6,087	$6,646
Lifetime net savings[f]	$524	$1,187	$1,690	$1,503	$727
Lifetime global warming pollution savings[g] (tons)	15.4	29.3	51.9	61.3	68.7
Cost-effectiveness (net cost per ton of CO_2-equivalent emissions)	-34.1	-40.5	-32.5	-24.5	-10.6
Lifetime oil savings[h] (barrels)	18.4	48.0	95.9	115.6	131.3
Cost-effectiveness (net cost per barrel of oil)	-28.4	-24.7	-17.6	-13.0	-5.5

NOTES:

a. Composite city/highway fuel economy over the EPA test cycle used in determining Corporate Average Fuel Economy (CAFE) compliance.

b. CAFE test results adjusted for the energy content in the fuel relative to gasoline.

c. Gasoline-equivalent CAFE results adjusted by 18% to better represent on-road performance.

d. Increase in manufacturer's suggested retail price. Excludes tax, title, and destination charges. Includes net costs to meet Tier 2, Bin 5 standards compared with baseline vehicle that meets the same emission levels.

e. Lifetime fuel cost savings based on the difference between the baseline gasoline vehicle and the cases shown here. Includes the following assumptions: average gasoline price of $1.40 per gallon; average diesel price of $1.40 per gallon; 15-year average vehicle lifetime; annual mileage of 15,600 in the first year, declining by 4.5% per year, and modified by a 10% rebound effect based on the per-mile cost of driving; and real discount rate of 5% (equivalent to an 8% new car loan).

f. Lifetime net savings based on the difference between the increase in MSRP and the lifetime fuel cost savings.

g. Lifetime global warming pollution savings presented as carbon dioxide-equivalent emissions from the vehicle tailpipe and upstream fuel manufacturing and delivery. Emissions from vehicle manufacturing, refrigerant leaks, and other sources are not included. Emissions are based on the same vehicle lifetime and mileage estimates used to calculate lifetime fuel cost.

h. Lifetime oil requirement presented as the amount of oil required to make the gasoline or diesel fuel used during the vehicle's lifetime, incorporating the same life and mileage estimates used to calculate lifetime fuel cost.

Table B-9 **Impact of Improved Gasoline, Diesel, Conventional, and Hybrid Technology on a Mid-Size SUV (Ford Explorer)**

Vehicle Technology	Baseline	Moderate	Advanced	Advanced	Advanced
Vehicle Type	**Conventional**	**Conventional**	**Conventional**	**Mild Hybrid**	**Full Hybrid**
Gasoline					
CAFE-rated fuel economy[a] (mpg)	20.8	28.1	36.3	42.2	49.3
Gasoline-equivalent CAFE fuel economy[b] (mpgge)	20.8	28.1	36.3	42.2	49.3
Real-world fuel economy[c] (mpgge)	17.1	23.0	29.8	34.6	40.4
Fuel economy improvement from baseline		35%	75%	103%	137%
Incremental retail cost increase[d]		$735	$2,458	$3,818	$5,247
Lifetime fuel cost savings[e]		$2,576	$4,323	$5,178	$5,947
Lifetime net savings[f]		$1,841	$1,866	$1,360	$700
Lifetime global warming pollution savings[g] (tons)		29.2	48.9	58.6	67.3
Cost-effectiveness (net cost per ton of CO_2-equivalent emissions)		-63.1	-38.1	-23.2	-10.4
Lifetime oil savings[h] (barrels)		58.1	97.5	116.7	134.1
Cost-effectiveness (net cost per barrel of oil)		-31.7	-19.1	-11.7	-5.2
Diesel					
CAFE-rated fuel economy[a] (mpg)	27.4	33.3	46.5	54.0	63.1
Gasoline-equivalent CAFE fuel economy[b] (mpgge)	24.1	29.4	41.0	47.6	55.6
Real-world fuel economy[c] (mpgge)	19.8	24.1	33.6	39.1	45.6
Fuel economy improvement from baseline	16%	41%	97%	129%	168%
Incremental retail cost increase[d]	$2,100	$2,475	$4,142	$5,427	$6,856
Lifetime fuel cost savings[e]	$2,380	$3,785	$5,669	$6,352	$6,965
Lifetime net savings[f]	$280	$1,310	$1,527	$925	$108
Lifetime global warming pollution savings[g] (tons)	10.7	29.3	54.3	63.3	71.5
Cost-effectiveness (net cost per ton of CO_2-equivalent emissions)	-26.3	-44.7	-28.1	-14.6	-1.5
Lifetime oil savings[h] (barrels)	7.4	46.9	99.8	118.9	136.1
Cost-effectiveness (net cost per barrel of oil)	-37.7	-27.9	-15.3	-7.8	-0.8

NOTES:

a. Composite city/highway fuel economy over the EPA test cycle used in determining Corporate Average Fuel Economy (CAFE) compliance.

b. CAFE test results adjusted for the energy content in the fuel relative to gasoline.

c. Gasoline-equivalent CAFE results adjusted by 18% to better represent on-road performance.

d. Increase in manufacturer's suggested retail price. Excludes tax, title, and destination charges. Includes net costs to meet Tier 2, Bin 5 standards compared with baseline vehicle that meets the same emission levels.

e. Lifetime fuel cost savings based on the difference between the baseline gasoline vehicle and the cases shown here. Includes the following assumptions: average gasoline price of $1.40 per gallon; average diesel price of $1.40 per gallon; 15-year average vehicle lifetime; annual mileage of 15,600 in the first year, declining by 4.5% per year, and modified by a 10% rebound effect based on the per-mile cost of driving; and real discount rate of 5% (equivalent to an 8% new car loan).

f. Lifetime net savings based on the difference between the increase in MSRP and the lifetime fuel cost savings.

g. Lifetime global warming pollution savings presented as carbon dioxide-equivalent emissions from the vehicle tailpipe and upstream fuel manufacturing and delivery. Emissions from vehicle manufacturing, refrigerant leaks, and other sources are not included. Emissions are based on the same vehicle lifetime and mileage estimates used to calculate lifetime fuel cost.

h. Lifetime oil requirement presented as the amount of oil required to make the gasoline or diesel fuel used during the vehicle's lifetime, incorporating the same life and mileage estimates used to calculate lifetime fuel cost.

The Diesel Dilemma

DIESEL'S ROLE IN THE RACE FOR CLEAN CARS

Diesel passenger vehicles have historically experienced low sales in the United States and have been stigmatized as "dirty." However, increasing concerns over U.S. oil dependence and climate change have prompted renewed interest in diesel technology. To reduce oil use, toxic pollution, and global warming—while saving money at the pump—should Americans invest in diesel- or gasoline-powered cars and light trucks?

This report provides a new analysis of the cost, fuel economy, and emissions performance of conventional, advanced, and hybrid-electric diesel and gasoline cars. Compared with today's conventional gasoline cars, our findings indicate that diesel can save consumers money over a vehicle's lifetime. Diesel cars are becoming much cleaner, but key emissions questions and challenges remain. Furthermore, improved gasoline vehicles are more cost-effective than diesel for reducing oil use and lowering global warming pollution.

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