DELIBERATING DIESEL:

ENVIRONMENTAL, TECHNICAL, AND SOCIAL FACTORS AFFECTING DIESEL PASSENGER VEHICLE PROSPECTS IN THE UNITED STATES

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EXECUTIVE SUMMARY

In 2002, less than one-half of one percent of cars sold in the United States was diesel vehicles, and there were no light-duty diesel trucks produced. This is in large part a legacy of the 1970s and 1980s, when light-duty diesels appeared in substantial numbers and were plagued by poor performance, unreliability, noxious exhaust, and high noise levels. Manufacturers have come a long way in addressing these shortcomings in recent years, however, and diesels can offer fuel economy and performance advantages over gasoline vehicles. In Europe, diesels now capture 40 percent of the passenger vehicle market. This report investigates the prospects for re-growth of diesel's share in the U.S. light-duty market.

The attractions of diesel are such that U.S. automakers have stepped up investment in a new generation of diesel vehicles. The fuel economy of today's direct-injection diesels can be 50 percent higher than comparable gasoline models. No federal mandate at present calls for fuel economy improvements of anything approaching this magnitude, but manufacturers may be interested in using diesel's efficiency advantage to allow them to make further shifts toward heavier light trucks without exceeding the Corporate Average Fuel Economy standard.

Diesel vehicles' energy advantage translates into smaller, but still highly significant, reductions in full fuel-cycle greenhouse gas emissions and petroleum consumption relative to gasoline vehicles. In addition to these energy-related benefits, diesels provide high power at low engine speeds, which is useful for towing heavy loads. For this reason, diesels are already prominent in the U.S. medium-duty passenger vehicle market.

The disadvantages of diesel vehicles still constitute major obstacles to increased presence in the United States, however. Their emissions of certain harmful pollutants remain much higher than those of gasoline vehicles due to intrinsic properties of diesel engines and fuel. Nitrogen oxides (NO_x), particulate matter (PM), and air toxics, in particular, are all strongly associated with diesel vehicles and have major direct and indirect public health impacts. NO_x is generally the most important precursor to smog formation in the United States. PM, especially the very fine particles that make up diesel exhaust, is a major factor in respiratory illness. California has designated diesel PM as a toxic air contaminant, and various studies there have found diesel emissions to be the cause of most cancers attributable to air toxics.

Diesel vehicles are also more expensive than gasoline vehicles. The price premium for cars is well over one thousand dollars relative to similar gasoline cars, and the differential for passenger trucks is several thousand dollars. Some diesel costs may decline slightly with higher sales volumes, but the technologies needed to lower tailpipe emissions will add new costs. In addition, the general public in the United States is thought to be quite skeptical of diesels' reentry into the passenger market owing to the flaws of earlier models.

Many auto industry leaders are optimistic that diesels can meet these challenges. New tailpipe emissions standards will begin to test—though not fully determine—the feasibility of making diesels as clean as gasoline vehicles. These federal "Tier 2" tailpipe standards, which will be phased in over the next 5 years, are far more stringent than earlier standards and, for the first time, hold diesel and gasoline vehicles to the same standards.

Under Tier 2, vehicles will be permitted to meet a range of standards, but each manufacturer's vehicles must achieve the same average NO_x level. While it will therefore be possible to sell diesel vehicles that do not meet this NO_x average, such sales will require offsetting sales of cleaner-than-average vehicles that will be difficult to achieve in large numbers. Dozens of gasoline vehicles have already been certified to meet some level of Tier 2 standards, but diesels have not been shown to meet any of these levels for the full 120,000 miles of operation the new standards require.

A prerequisite for diesel vehicles to reduce emissions dramatically is fuel with very low sulfur content, which permits the operation of emissions-reduction technologies that today's diesel fuel precludes. Most diesel fuel will be required by law to achieve this low sulfur level by 2006. The likelihood of diesels meeting or approaching average Tier 2 emissions performance will rise markedly at that point. In the meantime, the sale of diesels in certain vehicle classes will still be feasible to some degree, owing to features of Tier 2 that make compliance easier during the phase-in period.

In addition to cleaner fuel, major improvements on the vehicle side are required as well. There has been much progress in emissions-reduction technologies, both engine design and exhaust after-treatment. Multiple technologies under development can in principle eliminate the vast majority of NO_x and PM emissions. It is difficult to know which will be most successful ultimately, due to the complex interactions of the technologies and the hurdles they face, which include conflicts between NO_x and PM reduction, fuel economy penalties, and high cost.

It is cost, in fact, that will be most important to the future of diesels. There is little doubt that manufacturers can meet the emissions challenges in the next decade, but this will add to the vehicles' already high cost. Superior fuel economy could offset some of these costs through fuel savings, but not all. Even without the added emissions control costs future diesels will incur, it takes at least 4 years to recover the incremental purchase cost of today's diesel cars, and over twice that long for trucks. But given that diesels are already popular in the medium-duty weight market despite their high costs, other attributes clearly work in favor of these vehicles as well.

To predict the future of diesels in the United States, it is tempting to look to Europe, where they are rapidly gaining in the passenger vehicle market. Important policy differences make the comparison misleading, however. High fuel prices, financial incentives to reduce greenhouse gas emissions, and tailpipe standards less stringent than those in the United States produce a climate considerably more favorable to diesel in Europe.

Nonetheless, rapid technological advances in Europe spurred by diesel vehicles' popularity there do provide a glimpse of the state-of-the-art technologies that manufacturers will be looking to push still further in the United States. Regenerating particulate traps, advanced fuel injection systems, and integrated NO_x/PM control devices are all appearing in production models in Europe. None has yet been shown to fully meet Tier 2 average requirements, however.

Meanwhile, U.S. manufacturers have waxed hot and cold about expanding their diesel offerings, but are nonetheless clearly moving in that direction. Detroit plans to enter the light-duty diesel market within the next two model years.

Conclusions

Diesel vehicles may offer an important opportunity for increasing the fuel economy of U.S. passenger vehicles, but significant questions remain unanswered. With regard to the feasibility of a major increase in diesel's market share, key questions are: (1) the timeframe for the manufacture of clean diesels; (2) the development of competing technologies; and (3) the cost of advanced diesels relative to gasoline vehicles. Timing is particularly important for trucks in the 6,000 to 8,500 lbs. range, where manufacturer interest and market opportunity may be largest, but no products with encouraging emissions performance have emerged. In the coming years, hybrid vehicles will be the most likely competitor to diesels as high-efficiency vehicles. Hybrids' environmental performance is better, and they can clearly be regarded as a bridge to longer-term advances in vehicle technology. High cost will remain the largest hurdle for diesels as well as hybrids, unless fuel economy standards or fuel prices increase substantially.

Apart from the feasibility of a major increase in diesel's market share, the societal benefits of such a development bear further consideration. The potential for energy savings and related benefits is large. On the other hand, diesel will not bring energy savings if its efficiency advantages are used simply to offset fuel economy declines elsewhere. Furthermore, air pollution concerns remain, even with Tier 2 standards in place. In particular, additional attention is warranted to the control of ultrafine particles and air toxics.

Policy implications of this review of the status of light duty diesel include:

- Standards or incentives to increase fuel economy will improve the prospects for diesel vehicles; increased diesel penetration in the absence of policies to raise fuel economy is unlikely to achieve energy savings.

- Facilitating production of diesel vehicles by relaxation of tailpipe emissions standards would be counterproductive.

- Policies to accelerate mandatory production of ultra-low-sulfur diesel will have limited effect; consideration of further reduction in the diesel fuel sulfur standard is warranted.

- Federal funds for research and development of light and medium-duty diesel vehicles should support work for which there are clear and ambitious fuel economy and emissions targets, including Tier 2 bin 5 or cleaner.

- Fuel economy-based tax incentives for diesel vehicles are not warranted, as diesel is a well-established technology. Any incentives to promote advanced emissions control should clearly target superior emissions performance.

ACKNOWLEDGEMENTS

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INTRODUCTION

Light-duty diesel vehicles are uncommon in the United States today, but the superior efficiency of diesel engines has caused renewed interest in these vehicles. This in turn has re-sparked the "diesel debate" among the industry, energy, and environmental communities. Stigmatized by not-too-distant memories of lackluster performance and acrid exhaust plumes, diesel technology offers both the allure of increased fuel economy and the threat of increased health hazards. While prior drawbacks of diesel engines, such as noise, inferior performance, and high exhaust levels, have been mitigated in recent years, diesels still lag far behind gasoline vehicles in the cleanup of harmful tailpipe emissions. Upcoming tailpipe emission standards add greatly to the challenges facing diesel technology.

U.S. automakers are clearly eager to step up production of diesels, in part because their success in the light-duty truck market would make compliance with fuel economy standards easier. While the viability of diesels in that market will be determined ultimately by the industry and consumers, government policy can influence the rate of growth, particularly in the near term. The focus of federal automotive research dollars, structure of energy tax incentives for vehicles, tax policy for fuels, and adherence to the schedule for new vehicle tailpipe standards all have implications for the future of light-duty diesels.

Diesel advocates suggest widespread diesel deployment as a solution to the energy and global warming concerns facing the United States, while others portray the promotion of diesel as a risky endeavor with potentially pernicious results. Health impacts, regulatory constraints, fuel quality, technological developments, and consumer attitudes are among the numerous issues that will determine the fate of diesels in the U.S. passenger vehicle market. This report takes a pragmatic look at both the benefits and drawbacks of diesels, and the challenges they face in the upcoming Tier 2 / LEV II regulatory environment.

WHY DIESEL?

The intrinsic advantages of diesel vehicles follow from fundamental differences between diesel compression ignition engines and gasoline spark ignition engines. In a conventional, gasoline-powered engine, a mixture of air and fuel is drawn into the engine cylinder, where it is compressed by the cylinder piston and subsequently ignited by a spark from the spark plug. The force of the explosion in the cylinder pushes the piston back, yielding a motion that is translated through the piston's connecting rod to the engine crankshaft. In order to maintain reliable ignition, however, the amount of fuel and air allowed into the combustion chamber is limited, reducing the engine's cycle efficiency.

Today's advanced diesel engines—so-called compression ignition direct-injection (CIDI) engines—operate somewhat differently. First, rather than an air-fuel mixture, only air is drawn into the cylinder. The air is compressed more than twice as much as in spark ignition engines, causing the temperature of the air to increase to over 600° Celsius. Fuel is then injected directly into the cylinder, spontaneously igniting due to the high temperature in the cylinder. This combination of higher compression and higher temperature results in a more forceful explosion in the cylinder than in a spark ignition engine—a major factor in improved efficiency.

Energy Efficiency and Related Benefits

Diesel engines' efficiency can translate into high fuel economy. The magnitude of the fuel economy advantage of a diesel vehicle over a gasoline vehicle depends on a variety of factors. One is the choice of vehicles to compare: attributes such as horsepower, torque, and acceleration will not occur in the same combinations in diesel and gasoline vehicles (as discussed further below), so identifying "comparable" vehicles is not straightforward. Also, both engine and emissions technologies affecting efficiency are evolving rapidly and on separate tracks for diesel and gasoline vehicles. This makes a generic comparison of the efficiencies of the two vehicle types potentially misleading. Nonetheless, certain quantitative observations can be made that are key to the case for greater use of diesels.

Many more models of diesel passenger vehicles are available today in Europe than in the United States. An evaluation of 24 matched pairs there found that indirect-injection diesel vehicles had 24 percent better fuel economy than gasoline vehicles on average, while turbocharged, direct-injection (TDI) diesel vehicles averaged 50 percent higher fuel economy (Schipper, Marie-Lilliu, and Fulton 2002). In the United States, most noncommercial diesels are full-size sport utility vehicles (SUVs) and pickups over 8,500 pounds gross vehicle weight (GVW). Fuel economy data is not generally available for these vehicles, because they are above the weight range in which fuel economy standards apply. One manufacturer claims to have a developed a diesel light truck achieving a fuel economy 60 percent higher than the gasoline model (Stang 2002). Among cars, the only diesels sold in the United States today are manufactured by Volkswagen. These are TDI diesels that have a fuel economy ranging from one-half to two-thirds higher than their closest gasoline match.

Thus the fuel economy advantage of diesel can be quite substantial, especially given the increasing prevalence of direct-injection diesels. It should be noted, however, that advanced gasoline engine technologies could also bring significant fuel economy gains in the near future, reducing diesel's advantage somewhat. Engine technologies already in production have the potential to yield a 15–20 percent improvement in fuel economy relative to a typical gasoline vehicle today (DeCicco, An, and Ross 2001).

The higher fuel economy of diesels is not entirely attributable to efficiency. Diesel fuel contains about 11 percent more energy per gallon than gasoline (Wang 2001). A fuel economy advantage of 50 percent for a direct-injection diesel thus becomes a 35 percent advantage on a miles-per-Btu[1] basis. This is turn translates into savings of 26 percent in fuel energy per mile driven.

Additional energy considerations are associated with "upstream" activity, including refining of petroleum, transport of crude oil and finished product, and so forth. Diesel is a less refined petroleum product than gasoline, and consequently requires less energy to produce. The energy used to produce a given quantity of diesel fuel is one-fifth of the energy content of the

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[1] Btu = British thermal unit.

fuel; for gasoline, the ratio is one-fourth. As a result, the energy savings of a diesel over a gasoline vehicle on a full fuel-cycle basis are slightly higher than the savings for the vehicle use phase alone. The GREET model of the Argonne National Laboratory (Wang 2001) leads, under a set of reasonable assumptions, to the results shown in Table 1. The energy requirements of refining are somewhat higher for low-sulfur diesel (defined here as containing 50 parts per million [ppm] of sulfur) and reformulated gasoline than for their conventional counterparts; the energy advantage of diesel over gasoline for these advanced fuels remains about the same. The ultra-low-sulfur diesel required by regulation in 2006 will be limited to 15 ppm sulfur, however, which may require an increase in refining energy of several percent (Weiss et al. 2000), which would reduce diesel's energy benefit.

Table 1: Full Fuel-Cycle Performance of Diesel Vehicles Relative to Comparable Gasoline Vehicle

Fuels Used	Energy	GHG Emission	Petroleum
Conventional diesel/conventional gasoline			
Assume 25% higher fuel economy for diesel	-15%	-11%	-11%
Assume 50% higher fuel economy for diesel	-29%	-26%	-26%
Low-sulfur diesel/federal reformulated gasoline			
Assume 25% higher fuel economy for diesel	-14%	-10%	-2%
Assume 50% higher fuel economy for diesel	-28%	-25%	-18%

Source: Based on results from Wang (2001)

Two principal reasons for focusing on a vehicle's energy consumption and fuel economy are the related but distinct issues of greenhouse gas emissions and petroleum use. Greenhouse gas emissions—primarily carbon dioxide (CO_2), but including nitrous oxide (N_2O) and methane as well—on a CO_2-equivalent basis, are 6 percent higher per unit of energy for diesel than for gasoline (Weiss et al. 2000). Thus, the percent GHG reduction attributable to diesels is somewhat lower than the percent energy savings; the diesel vehicle having a 50% fuel economy advantage would emit about one-quarter less greenhouse gas than a gasoline vehicle. This reduction is more than sufficient to generate interest in increased use of diesel in the light-duty sector as a means of slowing global warming.

It should be noted that some recent research indicates that particles associated with the combustion of fossil fuels are a major contributor to global warming. Today's diesel engines produce relatively large amounts of such particles, and this research concludes that the net effect of increasing use of these diesels could be to accelerate climate change (Jacobson 2002). For future diesel vehicles, the need to comply with the more stringent emissions requirements now coming into effect (see "Quantifying the Emissions Challenge: Tailpipe and Fuel Standards," below) could mitigate this problem.

Like GHG savings, petroleum savings attributable to a diesel vehicle are also somewhat lower than energy savings, in large part due to the higher non-petroleum content of gasoline. As Table 1 shows, this is evident in particular in the case of federal reformulated gasoline, of which blending agents make up 10 percent (Wang 2001). These are largely non-petroleum ingredients, though fossil fuel-based.

The implications of increased use of diesel for petroleum consumption are complex. Both diesel and gasoline are typically produced from every barrel of oil that is refined, though the relative quantities of the two fuels can vary considerably. Any significant shift in the gasoline/diesel ratio of U.S. refineries' output raises a host of issues that are not within the scope of this report.

The intrinsic efficiency advantage of diesel vehicles does not necessarily lead to high fuel economy and reduced greenhouse gas emissions in the absence of policies to promote these outcomes. Indeed, many other efficiency improvements that have made their way into U.S. passenger vehicles over the past 15 years have allowed for increased size and power of the vehicles while maintaining the same fuel economy.

Performance

The compression ignition engine offers performance benefits beyond fuel efficiency. The more forceful combustion process of compression ignition engines, when translated from the piston through the mechanical components of the engine, results in greater torque (or circular force) in the rotating crankshaft. Engines with high torque offer better power at low engine speeds (revolutions per minute), which is important for towing heavy objects like boats or campers, and can move a vehicle quickly from rest. However, diesel engines traditionally have a lower peak horsepower than gasoline engines, which translates to lower top vehicle speeds and slower 0 to 60 miles per hour (mph) acceleration times. Hence the appeal of diesels is greater for larger vehicles. A wide disparity already exists between diesel car and noncommercial truck sales in the United States, as shown in Figures 1 and 3, and between domestic and import automakers, as shown in Figure 2.

While car-based diesel engines of the past have been criticized as faulty and hastily designed, most light- and medium-duty diesel trucks today utilize engines produced by heavy-duty engine manufacturers, who have more experience. Indeed, durability is often touted as another benefit of diesel engines. However, as the complexity of the diesel vehicle increases to meet tighter emission standards, durability may decline; emissions-control systems are far less durable than engines. At the same time that emissions-control equipment is being added to diesels, the durability of spark ignition engines has increased. The durability advantage of light-duty diesels is therefore diminishing, though it may persist to some degree.

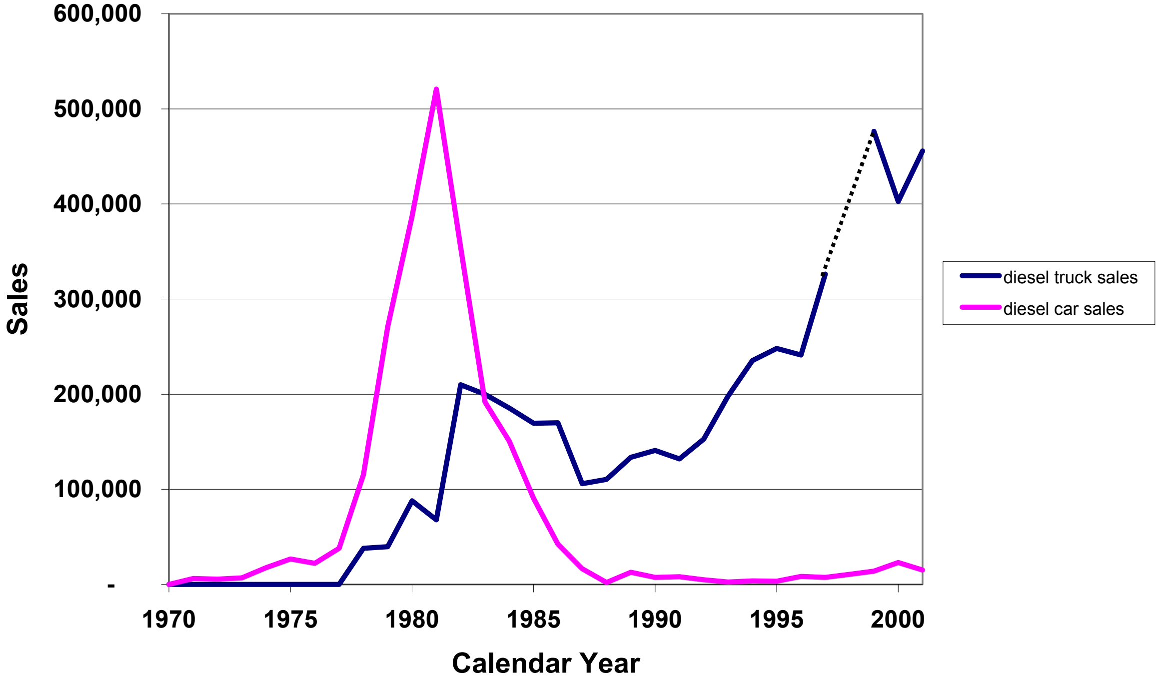
DIESEL CHALLENGES

The automotive industry faces a number of daunting challenges in bringing large numbers of diesel passenger vehicles to the U.S. market. Foremost among them are high production costs, stringent new emission standards, and skeptical consumers.

Cost

Diesel engines are more expensive than gasoline engines. Because they operate at higher compression ratios, diesel engines are built heavier, requiring more materials, which elevates their cost. Furthermore, as new features such as high-pressure common rail fuel injection and variable geometry turbine turbochargers are implemented to control emissions and elevate performance, their prices will likely continue to grow faster than the price of gasoline engines. Tomorrow's diesel vehicles also will require advanced after-treatment systems adding a significant cost, at least in the near term.

Figure 1: Diesel Car and Light Truck Retail Sales, 1970-2001

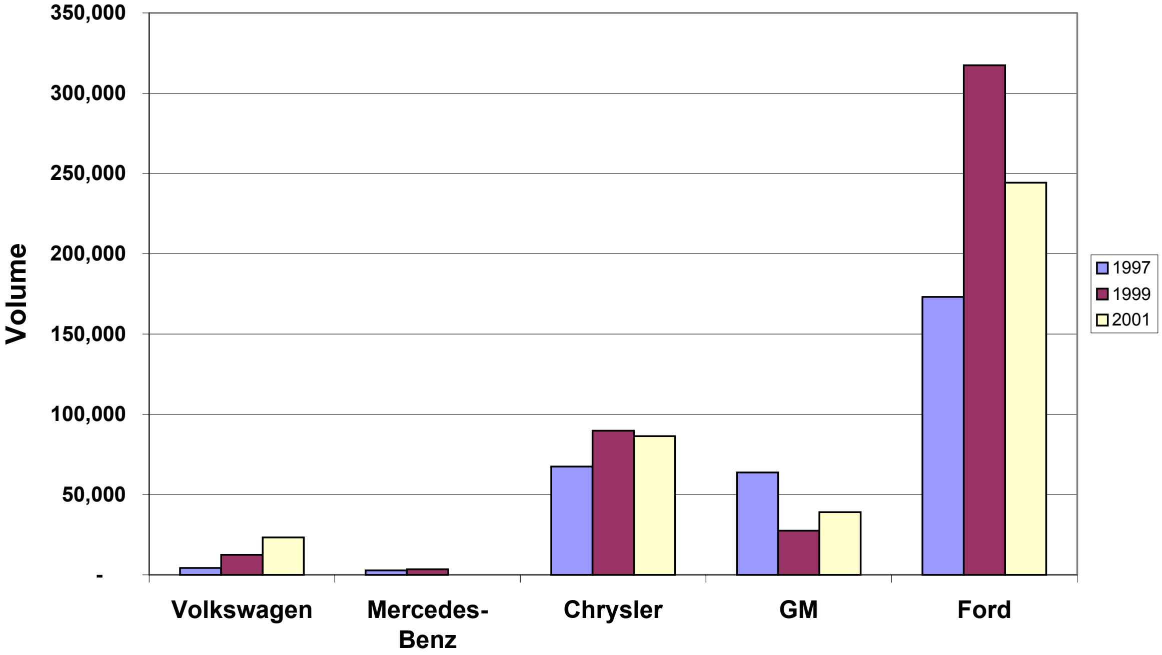


Sources: Davis (1999), years 1970–1979; Davis and Diegel (2002), years 1980–2001. Note: Anomalous 1998 data has been omitted.

Table 2 below shows the retail price differentials of the most comparable diesel and gasoline versions of models currently on the U.S. market. Diesel passenger vehicles primarily used for commercial purposes, such as Ford E-Series vans, are not included in our discussion. As noted above, the notion of comparable engines is not well-defined for diesel and gasoline vehicles. Matching horsepower will yield a different engine comparison than matching torque, for example. Where multiple comparison options exist, they are listed in Table 2. Figures 4 and 5 show the actual price difference, and the difference as a percent of purchase price, respectively.

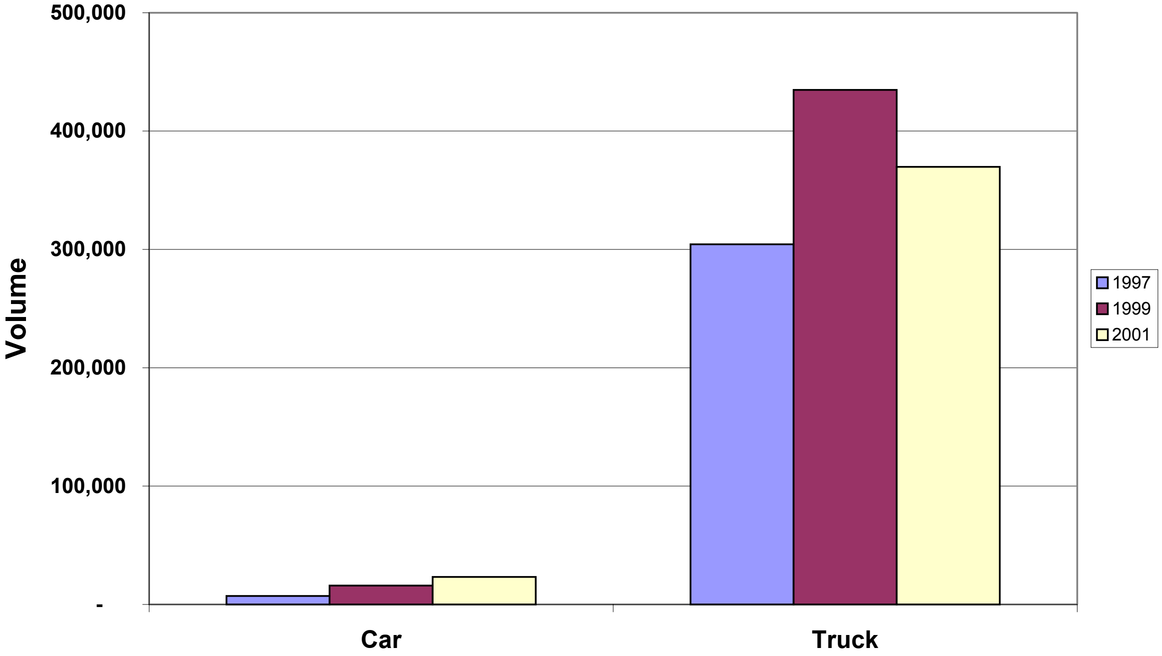
In summary, U.S. consumers pay $1,200 to $1,700 more for diesel cars today than for comparable gasoline models, while diesel medium-duty passenger trucks cost an additional $4,000 to $6,200. It should be noted, however, that a difference in price does not necessarily reflect a proportionate increase in cost to the manufacturer. The large disparity between cars and trucks in the price premium for diesel is explained to some degree by the difference in engine size, but also indicates the market's tolerance of greater profit margins on trucks.

Figure 2: Diesel Passenger Vehicle U.S. Sales by Manufacturer, Model Years 1997, 1999, 2001



Sources: Ward's Communications (1998, 2000, 2002)

Figure 3: Diesel Passenger Vehicle U.S. Sales by Vehicle Type, Model Years 1997, 1999, 2001



Sources: Ward's Communications (1998, 2000, 2002)

Table 2: Model Year 2003 Noncommercial Vehicles Available as Diesels

	Diesel Engine Specifications	Most-Comparable Gasoline Engine(s) Specifications	Diesel Cost Over Gasoline*
VW New Beetle	1.9L I4 turbo; 90 hp @ 3750 rpm; 155 lb-ft. @ 1900 rpm	2.0L I4; 115 hp @ 5200 rpm; 122 lb-ft. @ 2600 rpm	$1,180–$1,245
VW Jetta, Jetta Wagon, Golf	1.9L I4 turbo; 90 hp @3750 rpm; 155 lb-ft. @ 1900 rpm	2.0L I4; 115 hp @ 5200 rpm; 122 lb-ft. @ 2600 rpm	$1,180–$1,735
Ford Excursion	(a) 7.3L V8 turbo; 250 hp @ 2600 rpm; 525 lb-ft. @ 1600 rpm (b) 6.0L V8 turbo; 325 hp @ 3300 rpm; 560 lb-ft. @ 2000 rpm	(a) 5.4L V8; 255 hp @ 4500 rpm; 350 lb-ft. @ 2500 rpm (b) 6.8L V10; 310 hp @ 4250 rpm; 425 lb-ft. @ 3250 rpm	$3,870–$4,760
Ford F-250/350	6.0L V8 turbo; 325 hp @ 3300 rpm; 560 lb-ft. @ 2000 rpm [7.3L V8 turbo; 250 hp @ 2600 rpm; 525 lb-ft. @ 1600 rpm]**	5.4L V8; 255 hp @ 4500 rpm; 350 lb-ft. @ 2500 rpm 6.8L V10; 310 hp @ 4250 rpm; 425 lb-ft. @ 3250 rpm	$4,485–$5,470
Chevrolet Silverado, GMC Sierra 2500 HD/3500	6.6L V8 turbo; 300 hp @ 3100 rpm; 520 lb-ft. @ 1800 rpm	6.0L V8; 300 hp @ 4400 rpm; 360 lb-ft. @ 4000 rpm 8.1L V8; 340 hp @ 4200 rpm; 455 lb-ft. @ 3200 rpm	$4,160–$6,210
Dodge Ram 2500/3500	(a) 5.9L I6 turbo; 250 hp @ 2900 rpm; 460 lb-ft. @ 1400 rpm (b) 5.9L I6 turbo; 305 hp @ 2900 rpm; 555 lb-ft. @ 1400 rpm	(a) 5.7L V8; 345 hp @ 5400 rpm; 375 lb-ft. @ 4400 rpm (b) 8.0L V10; 305 hp @ 4000 rpm; 440 lb-ft. @ 2800 rpm	$4,025–$5,225

Source: MSN Autos (2003)

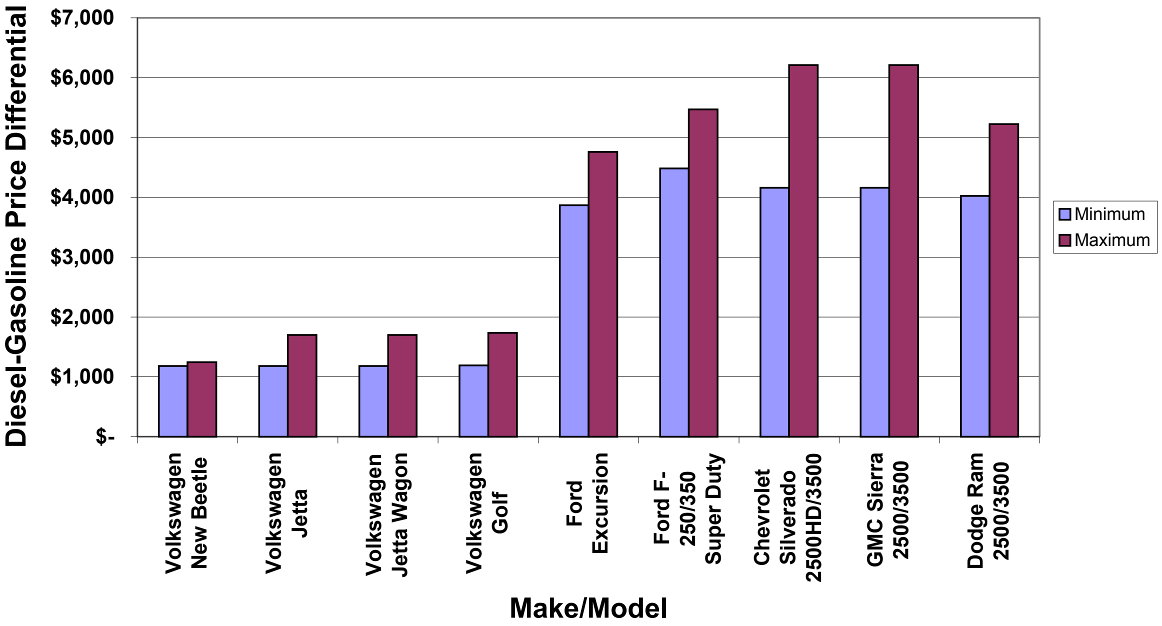
Note: In cases where more than one diesel engine is listed (i.e., Ford Excursion), the most comparable gasoline engine is identified by matching letter—"(a)" or "(b)." For listings with one diesel engine and two gasoline engines, cost differential includes comparisons to each gasoline engine.

*Cost differential applies to models with like trimline and transmission types.

**The 7.3L engine is only available on the F-Series Super Duty King Ranch, for which there was no MSRP information available. Cost differential information for this listing only applies to the 6.0L diesel engine.

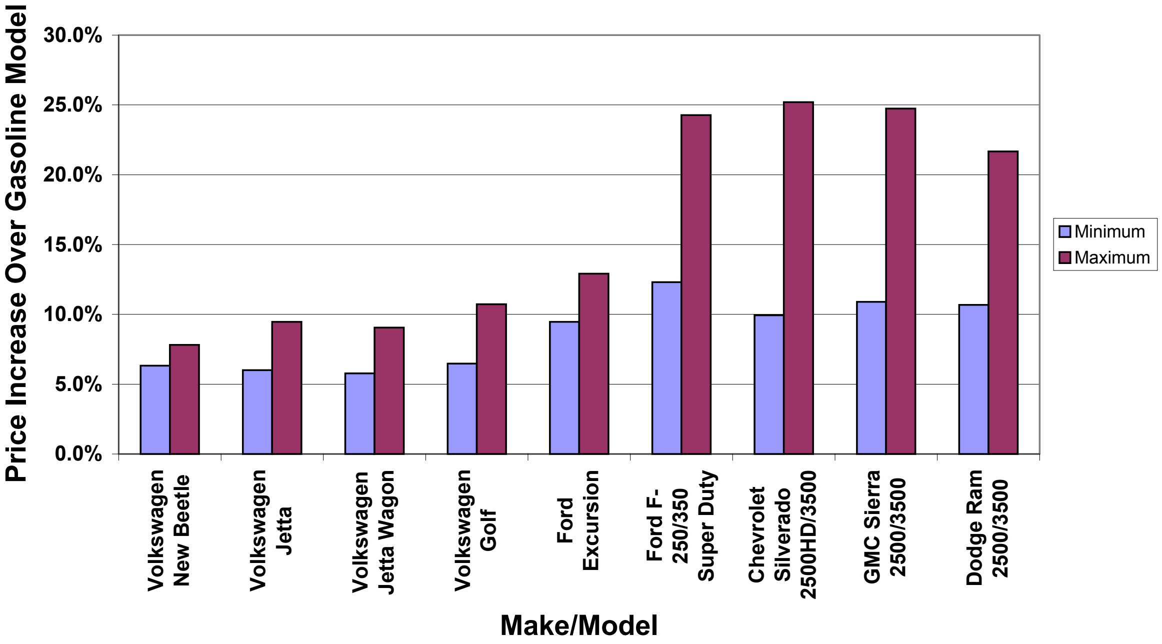
Diesel engines consume less fuel than gasoline engines, and diesel fuel historically has been slightly cheaper than gasoline in the United States. Thus annual fuel costs are lower for a diesel vehicle than for a comparable gasoline-powered vehicle. As discussed in "Market Prospects" below, however, it is unlikely that fuel savings alone could monetarily justify the purchase of diesels, particularly given that the ultra-low-sulfur diesel fuel necessary for clean diesel operation will be more expensive than today's diesel fuel.

Figure 4: Incremental Cost of Light Duty Diesel Vehicles: MSRP Differential between MY2003 Gasoline Models and Comparable Diesel Configurations



Sources: Edmunds.com (2003); MSN Autos (2003)

Figure 5: Incremental Cost of Light Duty Diesel Vehicles: MSRP Percent Change between MY2003 Gasoline Models and Comparable Diesel Configurations



Sources: Edmunds.com (2003); MSN Autos (2003)

Tailpipe Emissions

Respiratory ailments, cardiovascular disease, asthma aggravation, chronic bronchitis, decreased lung function, and increased lung cancer incidence have all been traced to diesel engine emissions (MECA 2002). Today's diesels still emit much higher levels than do gasoline vehicles of NO_x and PM, two of the most problematic pollutants associated with vehicle use in the United States today and the focus of the U.S. Environmental Protection Agency's (EPA) Tier 2 emissions regulations. In addition to these pollutants that impair respiratory function, diesel exhaust contains numerous known air toxics, and whole diesel exhaust has been identified as a toxic air contaminant by the California Air Resources Board and as a likely human carcinogen by EPA.

Here we outline the reasons for diesel vehicles' high emissions of these pollutants and summarize health concerns associated with diesel exhaust and its constituent emissions. We refer the reader to other sources for a thorough discussion of diesel-related health issues (CARB 1998; Shprentz 1996).

Nitrogen Oxides

A mixture of the compounds nitric oxide (NO) and nitrogen dioxide (NO_2)—more commonly known as NO_x—is created when nitrogen and oxygen gases in the engine cylinder combine under very high combustion temperatures. Because compression ignition engines produce higher peak flame temperatures in the cylinders than spark ignition engines, greater levels of NO_x are formed in diesel vehicles than in gasoline vehicles. In addition to being strongly temperature-dependent, NO_x formation is also affected by the concentration of oxygen in the cylinder and the duration of combustion (Stone 1999). While significant progress has been made in reducing NO_x from gasoline vehicles, minimizing diesel NO_x is proving to be a greater challenge.

Many advanced approaches, both in engine design and in after-treatment devices, are being investigated to reduce the level of NO_x emissions from diesel vehicles. One significant technical hurdle, however, is that techniques to lower peak temperature and reduce NO_x emissions often result in increasing PM emissions due to less complete combustion. Of the two pollutants, NO_x is viewed by the industry as the more difficult to control, so such techniques can be valuable despite this problem.

A host of environmental and health ailments can be attributed to emissions of NO_x. Aside from being a respiratory irritant itself, NO_x is a precursor to urban ozone (smog), a precursor to acid rain, and a contributor to nitrification (or over-fertilization) of bays and wetlands. A considerable portion of the U.S. population is now exposed to higher-than-acceptable levels of ozone. In early 2001, more than 109 million people living in 272 counties across the nation were exposed to ozone levels that exceeded the National Ambient Air Quality Standards (NAAQS) (Yacobucci et al. 2001). According to EPA's 2001 summary of air quality trends, national emissions of NO_x have increased 9 percent over the past 20 years, with diesel vehicles being one of the primary culprits of the emissions increase (EPA 2002a). Inventories show a modest decline over the past 5 years, however (EPA 2003a).

Particulate Matter

Physical characteristics of the compression ignition engine elevate PM emissions as well. Although CIDI engines operate in a lean (excess air) environment, low levels of oxygen in the immediate vicinity of the injected fuel spray prevent complete combustion of the fuel, resulting in the creation of unburned carbon particles, or soot. These carbon particles become coated with various compounds (primarily unburned molecules of hydrocarbon fuel and sulfuric acid aerosols) either during the combustion process in the cylinder or during the particles' ensuing flow through the vehicle's exhaust plumbing (MECA 2002). This coating acts as a glue to which other compound-coated particles can adhere.

Emissions of fine particles from vehicles are a key concern for environmental and public health advocates. The size, as well as the composition, of particles in diesel exhaust is an important determinant of their health impacts. Concerns about PM have shifted their focus in recent years as awareness has grown of the particularly harmful effects of particles small enough to make their way deep into the lungs. In 1997, EPA added a new air quality standard for particulate matter with a diameter of 2.5 microns or less ($PM_{2.5}$) to the earlier standard for particles under 10 microns (PM_{10}). As of 2001, nearly 73 million people lived in counties that were in violation of federal health-based air quality standards for $PM_{2.5}$ (EPA 2003b).

It is important to distinguish among particles at still finer levels. A very high fraction of diesel particle emissions are nanoparticles (i.e., those under $5x10^{-8}$ meters in diameter), which are not regulated. Concentrations of nanoparticles pose a serious public health risk, as their small size and damaging nature pose a double-threat: the compounds are in some cases cancer-causing and are small enough to lodge themselves deep into lung tissue, where a large portion of them remain (MECA 2002).

The larger (40–200 nanometers, or $4x10^{-8}$ to $2x10^{-7}$ meters, in diameter) of these ultrafine carbon soot particles, sometimes called "accumulation mode" particles, are fairly well understood and have been consistently measured in laboratory tests. However, the concentration of smaller particles (10–50 nanometers in diameter), sometimes referred to as "nucleation mode" nanoparticles, in diesel exhaust can vary by two to three orders of magnitude, depending on such factors as temperature, humidity, fuel type, and exhaust gas dilution level. For example, recent exhaust plume studies have indicated that nucleation mode nanoparticles increase with higher fuel sulfur content, or with a decrease in the air temperature (T.V. Johnson 2002a). Even more recent research showed a strong emerging correlation between the fraction of nanoparticles (<50 nm) and unburned lubricating oil (T.V. Johnson 2003).

Air Toxics

The toxicity of diesel exhaust follows from both the quantity and the chemical properties of the PM it contains, and from the presence of numerous gaseous toxic substances in relatively high concentrations. The high level of particle emissions relates to diesel engine properties, as discussed above, while the toxic chemical content of the exhaust follows from characteristics of diesel fuel, a product that is less refined than gasoline.

In 1998, the state of California deemed diesel PM to be a toxic contaminant because of its potential to cause cancer and other ill-health effects. A 1999 study by California's South Coast Air Quality Management District (AQMD) supported this conclusion with findings that diesel emissions are responsible for 71 percent of the estimated cancer incidence from urban air toxics in the greater Los Angeles area (SCAQMD 1999). Over and above PM, diesel exhaust contains more than 40 cancer-causing diesel substances (CARB 2000a). An assessment by EPA of the health effects of diesel emissions concluded that "diesel exhaust is likely to be carcinogenic to humans by inhalation at any exposure level" (Federal Register 2002).

Consumer Perception

Consumers' substandard experiences with diesel vehicles in the 1970s and 1980s have led to poor perceptions of them that persist to this day. Today's automotive engineers are having considerable success in addressing the dirty, noisy, and noxious qualities of diesel engines, and overcoming negative consumer perceptions will be critical for higher light-duty diesel penetration—especially for passenger cars—in the U.S. market.

Analysts have argued that while fuel prices contributed to both the rise and the fall of light-duty diesels in the United States historically, poor vehicle quality also played a role in their decline. As the economic advantages of high fuel economy disappeared with declining fuel prices, negative aesthetic aspects of diesel cars placed them at a disadvantage to conventional gasoline cars (Truett and Hu 1997). Fuel prices may rise again, but significant penetration in the U.S. market will require that these drawbacks of diesels be eliminated.

QUANTIFYING THE EMISSIONS CHALLENGE: TAILPIPE AND FUEL STANDARDS

New federal and California emissions standards will require very significant reductions in tailpipe pollution. Attaining the new standards is expected to be quite straightforward for gasoline vehicles, except perhaps the largest among them (Federal Register 2000). For diesels, however, the standards pose a major challenge, even though key features of the standards were designed specifically to facilitate compliance by diesel vehicles.

In order to make the new emissions standards flexible, numerous complexities and details have been incorporated into the regulations. The discussion below addresses only those features of the standards that are particularly pertinent to the development of the U.S. diesel vehicle market. In particular, we focus on NO_x and PM, even though emissions of hydrocarbons, carbon monoxide, and formaldehyde are regulated as well. NO_x and PM not only are the two primary pollutants associated with diesel vehicles, but also are regarded as the two most problematic of the regulated mobile source emissions. Nanoparticles and many air toxics associated with diesels remain unregulated.

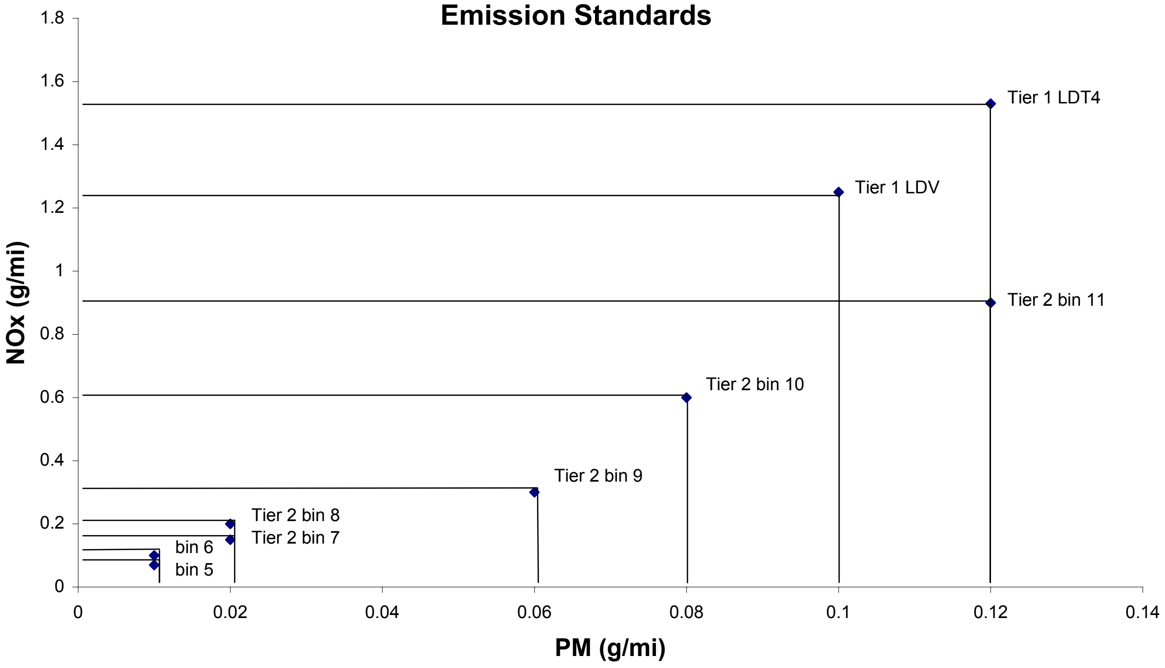
Federal Emissions Standards

Since 1990, light-duty vehicles have been required to meet federal "Tier 1" emission standards. In acknowledgement of the difficulty of controlling NO_x emissions in diesel engines, Tier 1 allows diesels to emit up to 2.5 times more NO_x (depending on vehicle size) for the first 50,000 miles of life than their gasoline-powered Tier 1-certified counterparts. Moreover, the vast majority of new gasoline vehicles meet the LEV (Low Emission Vehicle) standard, which is more stringent than Tier 1. For PM, diesels are subject to either a 0.1 or a 0.12 grams-per-mile (g/mi) full-useful-life standard under Tier 1. Gasoline vehicles have not been tested regularly for PM but generally emit quantities of PM much smaller than this.

With model year 2004, EPA will begin a 6-year phase-in of more stringent "Tier 2" emissions standards for light-duty vehicles and medium-duty passenger vehicles (MDPVs—i.e., those between 8,500 and 10,000 lbs. GVW). Diesels and gasoline vehicles will be subject to the same set of standards. Tier 2 ratchets down the Tier 1 full-life NO_x standard for diesel cars and light-duty trucks by at least 80 percent and, for PM, by 75 percent. Unlike Tier 1, the Tier 2 standards, when fully phased in, will apply equally to passenger cars, light trucks (minivans, pickups, and SUVs), and MDPVs.

Another fundamental change introduced by Tier 2 is that, rather than simply setting an upper bound for a vehicle's emissions of each pollutant, the standard is an average NO_x level, which each manufacturer's vehicles must attain. The system is implemented by placing each vehicle into one of eleven "bins," which are defined by a maximum level for each covered pollutant. The NO_x values for the bins into which a manufacturer's vehicles fall must average to the standard. The bin system introduces flexibility into the scheme by allowing automakers to sell models that emit higher levels of NO_x and balance those emissions with sales of models that emit lower-than-average levels. As the phase-in progresses, an increasing percentage of vehicles sold are required to meet the NO_x averaging requirement. Figure 6 and Table 3 show NO_x and PM emission standards for each of the Tier 2 bins.

Figure 6: Tier 1 Light-Duty Diesel and Tier 2 Full Useful Life Exhaust Emission Standards



Source: Federal Register (2000)

Table 3: Tier 2 NO_x and PM Full Useful Life (120,000 miles) Emission Standards

Tier 2 Bin Number	Valid Through (Model Year)	NO_x (g/mi)	PM (g/mi)
bin 11 [a]	2008	0.9	0.12
bin 10	2006	0.6	0.08
bin 9	2006	0.3	0.06
bin 8	-	0.20	0.02
bin 7	-	0.15	0.02
bin 6	-	0.10	0.01
bin 5	-	0.07	0.01
bin 4	-	0.04	0.01
bin 3	-	0.03	0.01
bin 2	-	0.02	0.01
bin 1	-	0.00	0.00

Source: Federal Register (2000)

[a] Available only to MDPVs.

Because the emissions levels associated with the bins decline rapidly with declining bin number, any high bin vehicle sold will need to be offset by multiple cleaner-than-average vehicles. Thus, for example, in order to sell a single bin 8 vehicle, a manufacturer would need to sell two bin 3 vehicles and one bin 2 vehicle given the 0.07 g/mi NO_x average requirement. Note however that the average PM value for this set of vehicles exceeds the bin 5 value (0.01 g/mi); the Tier 2 averaging scheme permits this.

The challenge Tier 2 poses for diesel vehicles is widely acknowledged in the industry. Representatives from seven of the top automakers indicated in interviews that no diesel vehicle they currently produce is able to meet Tier 2 requirements fully.

Tier 2 “interim” standards are another matter. Between 2004 and 2008, a certain percentage of each manufacturer's vehicles, which decreases annually, is subject to a NO_x requirement less stringent than the Tier 2 average. This subset of a manufacturer’s production may include vehicles not clean enough to fall into any of the permanent Tier 2 bins. In fact, NO_x emissions of 0.6 g/mi—eight and a half times the bin 5 level—will still be allowed for a portion of an automaker’s light-duty vehicles, while 0.9 g/mi—nearly thirteen times the bin 5 level—will be permitted for MDPVs prior to 2009.

Similarly, PM emissions of 0.08 grams per mile—only slightly below the Tier 1 standard and four times the PM standard for the least stringent permanent bin (bin 8)—will be permitted for a limited percentage of cars and light trucks through 2007. Growth in diesel sales could be accommodated over the next few years in this less strictly controlled portion of a manufacturer’s production. Furthermore, in the interim period, automakers have the option of certifying a portion of their MDPVs to less-stringent heavy-duty engine standards rather than Tier 2 vehicle standards. MDPVs also have no on-board diagnostics (OBD) requirement in general under Tier 2 (Federal Register 2000), so there is less assurance that these vehicles will function as intended on-road and over the life of the vehicle.

California Emissions Standards

The federal Tier 2 program discussed above was based on California's LEV II vehicle emissions program, which was adopted in 1998 and, like Tier 2, will be phased in between 2004 and 2009. LEV II differs from the Tier 2 program in certain important respects, however. First, while the Tier 2 averaging scheme is based on NO_x, LEV II imposes a fleet-averaging scheme based on hydrocarbons (NMOG) only, while requiring every vehicle to meet the average Tier 2 NO_x value of 0.07 grams per mile (CARB 2000b). LEV II regulations also specify a 0.01 g/mi full-life (120,000-mile/11-year) PM cap for all light-duty cars and trucks, which is required only for bins 6 and below under Tier 2. Thus California's requirements for both NO_x and PM are more stringent than federal Tier 2 requirements.

While Tier 2 allows 2 additional years for heavier light-duty trucks (6,000–8,500 lbs. GVW) to meet the final 0.07 g/mi NO_x standard than passenger cars, LEV II requires these vehicles to follow the same timeline. Lastly, while final Tier 2 standards apply equally to all vehicles up to 10,000 lbs. GVW, LEV II requirements are less stringent for MDPVs. California regulations, however, prohibit models from being California-certified if cleaner versions are certified federally (CARB 2001).

Sulfur Standards

The maximum allowable sulfur content in highway diesel fuel nationally is now 500 ppm. The current sulfur level in diesel fuel is approximately 250 ppm on average (Wang 1999). Because cleaner fuel is a critical component of advanced clean diesel vehicles, EPA's Tier 2 regulation places a sulfur cap of 15 ppm at refineries by June 1, 2006, and at retail locations by September 1, 2006.

The EPA rule allows refiners a degree of flexibility in meeting the 15 ppm standard, which will result in some sales of fuel containing high sulfur levels through the end of the decade. A 3.5-year transition period (from June 1, 2006 through the end of 2009) allows refiners to produce up to 20 percent of their highway diesel fuel at current sulfur levels (up to 500 ppm), as long as it is segregated from the ultra-low-sulfur diesel fuel and is only used in pre-model year 2007 heavy-duty vehicles (EPA 2000).

Discussion

Fitting into the new emissions regimes will require major improvements in diesel vehicle emissions control. Adding considerably to the challenge of the emissions levels is the required durability of 120,000 miles for the full-useful life standards. Given recent progress in emissions control technology, however, it is likely that diesels will soon be able to meet the requirements for high Tier 2 bins. The wide availability of low-sulfur diesel beginning in late 2006 should greatly facilitate further reductions in diesel emissions levels.

Allowing sales of high-bin diesels should not increase net NO_x emissions, given that such vehicles must be offset by sales of low-NO_x emitters in order to maintain the required NO_x average. There is no such averaging requirement for PM, however, and the average PM emissions of a group of high- and low-bin vehicles meeting the required NO_x average will be higher than those of a bin 5 vehicle, because the PM requirement is constant for bins 2 through 6. Increased sales of diesels can be expected to lead to an increase in PM emissions, both for this reason and because the gasoline vehicles they displace would emit less PM than is allowed in even the low bins.

In the very near term, manufacturers can be expected to take advantage of the full flexibility of Tier 2 and include diesels in the portion of their fleets not subject to the bin 5 NO_x average. There is no particular reason to assume that gasoline vehicles will do better with respect to NO_x in this period, but diesels falling into the interim bins (bins 9-11) will have PM emissions 3 to 6 times higher than those of any permanent bin.

The importance of LEV II goes beyond its role as a model for Tier 2: California represents over 10 percent of the passenger vehicle market and therefore is a significant driver of product development plans. Furthermore, California standards have been adopted by four Northeastern states; these five states together accounted for one-fifth of all U.S. passenger vehicle registrations in 2001 (Ward's Communications 2002). California requirements pose a more difficult challenge for diesels, especially in the short term. Many in the industry feel that the LEV II NO_x requirement of 0.07 grams per mile will effectively prohibit new light duty diesel vehicles in California for several years, although some automakers are clearly investigating their ability to meet the standard.

The sulfur content of diesel fuel has been a contentious issue. While EPA and most industry analysts conclude there are no significant technological barriers to achieving the sulfur levels of 15 ppm in diesel fuel required in 2006, representatives of most (though not all) of the refining industry have opposed such levels due to the associated costs (Yacobucci et al. 2001). According to a Congressional Research Service summary of cost assessments to date, the added cost of producing ultra-low-sulfur diesel will fall between 4.4 cents/gallon (EPA estimate) and 8.9 cents/gallon (American Petroleum Institute estimate), while distribution of the fuel would cost as little as 0.5 cents/gallon (EPA) up to 0.9 cents/gallon (American Petroleum Institute) in the long term (Yacobucci et al. 2001).

In keeping with the refining industry's cost concerns, there has been some speculation that certain refiners may choose not to produce ultra-low-sulfur diesel, leading to a shortage in 2006 and beyond. But EPA's recent proposal of a rule to dramatically reduce pollution from non-road sources, which requires the fuel for these engines to match the upcoming highway vehicle fuel level of 15 ppm sulfur by 2010, increases the incentive for refiners to make the investment needed to produce ultra-low-sulfur diesel.

In any case, the widespread availability of ultra-low-sulfur diesel fuel will be essential to bringing down the real-world emissions of early-introduction diesel vehicles. Tier 2 emissions testing may be performed with ultra-low-sulfur diesel fuel, so a vehicle's bin number can understate its actual emissions during this transitional period. Presumably, the use of certain after-treatment devices will await the arrival of the cleaner fuel, since high-sulfur fuel can damage them, in some cases irreversibly. Other emissions control technologies will be introduced now to meet Tier 2 requirements, however, even though their on-road performance will be compromised by today's sulfur levels.

MEETING THE EMISSIONS CHALLENGE: TECHNOLOGICAL PROGRESS

The auto industry has invested significant resources in addressing the challenges facing diesels, and progress has been impressive in some respects. Upcoming emissions regulations will nonetheless require considerable further progress for diesels to become a viable option for widespread passenger vehicle use. Advanced emissions control for diesel vehicles calls for a systemic approach involving the use of (1) sophisticated engine designs with low "engine-out" emissions, (2) advanced after-treatment technologies, and (3) clean, low-sulfur fuel.

The following discussion of engine and after-treatment emissions-control technologies is not intended to be exhaustive. Other authors have summarized the operation and control potential of contemporary diesel control technologies. Mark and Morey (1999) discussed projected emissions-reduction potential and fuel economy penalties associated with various after-treatment technologies as of the year of publication. More recent detailed comparisons of NO_x after-treatment systems were provided by T.V. Johnson (2002a, 2003). Here we highlight developing technologies that seem most promising for meeting new emissions requirements.

Engine Technologies

The first component of a clean diesel system is an advanced engine designed to minimize NO_x and PM emissions in the engine cylinders through combustion management. By altering the values of parameters such as fuel injection timing, injection pressure, or combustion gas temperature, automotive engineers are developing ways of reducing the levels of these pollutants before the exhaust reaches the after-treatment system. The NO_x/PM tradeoff mentioned earlier is a persistent theme in engine control techniques, however.

Today's diesels use direct injection (DI), which refers to the method by which fuel is inserted into the cylinders. Indirect-injection engines first mix fuel and air in a "prechamber" outside the cylinder to assist in fully diffusing the fuel into the air before it is injected into the main cylinder. Although indirect injection accommodates a thorough fuel/air mixture, it incurs a fuel economy penalty due to energy losses caused by the prechamber. Direct-injection engines overcome that fuel economy penalty by injecting fuel directly into the cylinder, yielding a significant efficiency gain.

Direct injection has been used in heavy-duty diesel engines around the world for quite some time. Until recently, however, the ability to use DI in smaller passenger vehicle engines was prohibited by the vehicles' need for much faster mixing of air and fuel, previously unobtainable without the use of a prechamber. Recent advances in injection control, however, have changed that. Direct-injection is now used in all diesel passenger cars, pickups, and SUVs currently on sale in the United States.

High-Pressure Fuel Injection

As noted earlier, more complete mixing of fuel and air in the cylinder minimizes the creation of fuel-rich areas that are the source of particle emissions during combustion. Today's high-pressure fuel injectors can spray fuel mist into the cylinders at extremely high pressures (around 20,000 to 30,000 pounds per square inch), accelerating diffusion and reducing engine-out emissions (S. Johnson 2002). Because of the importance of fuel injection with respect to engine performance and emissions, much research has been devoted to developing these high-pressure systems. They include hydraulic electronic unit injection (HEUI) and common-rail systems, among others.

Unit injectors in HEUI systems are controlled hydraulically by a high-pressure oil pump. The hydraulic system controls the rate of injection, and computer-controlled electronics control the overall amount of fuel that is injected into the cylinder (Stone 1999). Consequently, the speed or period of a cam lobe does not limit the injection process. HEUI injectors have been widely used domestically in medium-duty trucks such as the 7.3L Power Stroke diesel engine in Ford Super Duty pickups (Ford Motor Company 2002b; Stone 1999).

Another injection design, the common rail system, keeps fuel under pressure at all times so that high-pressure fuel injection can be obtained during any vehicle-operating condition. In this system, fuel is fed from a shared reservoir through a “common rail” to all of the cylinders. This allows high atomization of the fuel in order to reduce PM emissions. Common-rail systems, while not currently in use in the United States, are now widely used in European passenger cars. Such expensive systems are more cost-effective in larger engines (6 cylinder and up), where they can replace a greater number of unit injectors (S. Johnson 2002).

Electronic Fuel Injection

In older diesel engine systems, the timing and amount of fuel injected into the cylinder were determined by mechanical operation: higher loads on the engine caused injections of greater amounts of fuel, some of which was not completely burned. Consequently, these systems also produced higher levels of unburned fuels that were emitted as soot.

Advances in electronic fuel injection have enabled automotive engineers to now design engines that independently and precisely control the timing of the fuel injection with respect to the piston position, and the amount of fuel injected into the cylinder. Electronic sensors monitor the vehicle’s actions and engine performance (such as exhaust temperature or combustion completeness), and adjust fuel injection parameters accordingly to control both NO_x and PM emissions.

One example of electronic injection control is so-called injection timing retard, where fuel is injected later than normal, lowering combustion temperature and reducing NO_x emissions. Injection timing retard, however, adversely affects fuel economy and PM emissions (Stone 1999). Other techniques, such as pilot injections or post-injections, are used to reduce emissions or “prime” the exhaust with excess hydrocarbons for more effective after-treatment control.

Cylinder Modifications

Modifications to the design of the cylinder that aid in the mixing of fuel and air reduce both NO_x and PM emissions. Examples of such modifications include changing the shape of the combustion chamber and piston bowl, increasing the number of valves per cylinder, and incorporating spiral-shaped intake ports to increase “air swirl.”

Turbocharger Advancements

The function of turbochargers is to boost the engine output by compressing air entering the cylinder. Physically, a turbine powered by the engine’s exhaust drives the compressor. By squeezing more air into the chamber, turbochargers provide the engine with greater power, as the additional air accommodates the addition of more fuel. Turbocharging improves performance while reducing PM due to the additional air in the cylinder. However, it also increases the temperature of the intake air, which, in addition to elevating NO_x production, works against the intended goal of increasing air density.

To address this issue, sophisticated systems have been developed that include, for example, “air-to-air charge cooling,” which cools the charged air with ambient air (rather than a water-based system). Cost and complexity limit use of these systems, however (Stone 1999). Another advanced turbocharger design, variable geometry turbines (VGT), separates the power of the turbine from the force of engine exhaust so that the turbocharger can be optimized in a variety of operating conditions. VGT is common in European light-duty models (DTF 2001a).

Exhaust Gas Recirculation

Exhaust gas recirculation (EGR) is the technique of redirecting a portion of the exhaust gas back into the engine cylinder to dilute the combustible gas and reduce the peak flame temperature. Like other temperature-reduction techniques, this reduces NO_x emissions but tends to increase PM emissions.

EGR is common in today’s vehicles. However, advances in EGR, such as electronically controlled EGR or cooled EGR (where the exhaust gas is first cooled), are being developed, though these advances add cost and complexity.

The effect on nanoparticle concentrations of EGR and other diesel engine design improvements, such as high-pressure fuel injection and flexible injections, is still unclear. Recent laboratory research indicates that increased injection pressures reduces nanoparticle concentrations and average size, while EGR appears to increase nanoparticle concentrations. Homogeneous charge compression ignition (HCCI) engines, which offer great promise in reducing both NO_x and PM, have been shown to reduce overall particle mass but are unable to reduce nanoparticle concentrations (T.V. Johnson 2002a). Some research has indicated that future technology trends will include higher levels of EGR, which will result in an overall PM emissions shift to smaller particle size (Gupta 2002). In summary, researchers’ understanding of the complex nature of these emissions continues to improve, but continued work is necessary to develop appropriate methods to further reduce particle emissions.

After-Treatment

The second component of emissions control is after-treatment technology, aimed at reducing the pollution in the exhaust stream before it exits the vehicle's tailpipe. A number of technologies have been developed for this purpose, and some automotive researchers believe that after-treatment technologies will eventually allow diesel to reach emissions levels typical of gasoline systems. Engineering breakthroughs will be necessary to meet that goal, however (Tabaczynski 2001).

Diesel Oxidation Catalysts

Similar in physical design to a gasoline vehicle's three-way catalyst, diesel oxidation catalysts consist of a canister containing a precious metal-coated honeycomb substrate. As exhaust gases flow through the substrate, a chemical reaction between the gases and the coating oxidizes pollutants into less-harmful compounds. Like three-way catalysts, diesel oxidation catalysts are sensitive to sulfur poisoning. Oxidation catalysts help control carbon monoxide, hydrocarbons, and to a degree, PM emissions. They do not control nitrogen oxide emissions.

Oxidation catalysts are a common technology in today's diesel vehicles. These catalysts have been extensively used on heavy-duty diesel vehicles, and are currently being used on light-duty vehicles, including Volkswagen's TDI models in the United States.

Particulate Filters

Particulate filters, or traps, are devices placed in the exhaust stream to capture PM. Diesel particulate filters have been used in some heavy-duty applications for decades. The technology has evolved greatly over this period, and only recently have the filters become available for light-duty vehicles. These have shown much promise, though durability concerns persist, as do other issues related to fuel economy penalties, regeneration, and lube oil ash management (T.V. Johnson 2003).

While the filters can be quite effective at capturing PM emissions, they eventually become clogged. Consequently, the system must be capable of cleaning, or regenerating, the filter to alleviate "backpressure," which hampers engine performance and reduces fuel economy. One way of accomplishing this is by periodically injecting fuel into the exhaust stream at high temperatures to burn soot off of the filter. This detracts from the vehicle's fuel economy, however. Furthermore, if engine temperatures are not high enough to accomplish filter regeneration, alternative methods of generating heat (such as electrical heating systems) must be incorporated into the system (T.V. Johnson 2002a). In addition, the efficacy of filters in removing the smallest particles from the exhaust stream is not well understood. The high level of concern about health effects of ultra-fine particles in the United States and Europe means this will be an important determinant of the success of the technology.

While diesel particulate filters have not yet arrived in the U.S. light-duty vehicle market, they are likely to play a major role in meeting upcoming emissions standards, because they significantly outperform other technologies (Bertelsen 2001; T.V. Johnson 2002b). Research on filter efficiency and regeneration techniques is continuing, including efforts to integrate particulate filters and NO_x adsorbers (see below) into the same device (T.V. Johnson 2002a).

Lean NO_x Catalysts

Lean NO_x catalysts use injections of a hydrocarbon reductant (diesel fuel) into the exhaust stream to assist in reducing NO_x to nitrogen and water vapor in a lean environment. This is a potential low-cost solution to lowering emissions; however, peak conversion efficiencies for this technology are still less than 50 percent. Significant gains have been made in the past year on lean NO_x catalyst research, although emission of the reductant ("hydrocarbon slip") is still an issue. While the use of diesel fuel as a reductant is convenient, it results in fuel economy penalties on the order of 3 percent (T.V. Johnson 2002b).

NO_x Adsorber Catalysts

A second type of NO_x catalyst, NO_x adsorbers (also called NO_x traps), offers greater promise. This technology operates in two phases. First, nitrogen oxides in the exhaust stream chemically adhere to a "storage site" on the device, where they are adsorbed, or trapped. When all of the storage sites are filled, a hydrocarbon reductant is used to regenerate the device by releasing the trapped NO_x and converting it to nitrogen gas.

Adsorbers offer much higher NO_x conversion efficiencies (approximately 70–80 percent) and have a wide temperature range of peak operation. They also have fuel economy penalties comparable to those of lean NO_x catalysts, however, again from the use of diesel fuel as a reductant (T.V. Johnson 2002b). Though not currently used in the United States, NO_x adsorbers are likely to be a prominent control technology in future diesel vehicles. Thermal durability, sulfur sensitivity, and regeneration strategies each pose significant hurdles to wide-scale applicability of this technology, however (T.V. Johnson 2002a).

While the NO_x adsorber catalyst system looks promising for light-duty passenger cars and trucks, durability continues to be a concern, as sulfur in both diesel fuel and lubricating oil inhibits after-treatment performance. Much work remains before real-world application of the technology becomes viable, including addressing regeneration capabilities, high-mileage durability, transient control with on-board diagnostics, packaging, and cost issues. Cold start issues are also a concern, as diesel vehicles' comparatively cool exhaust can make reaching the catalyst's effective operating temperature difficult (Stone 1999).

Selective Catalytic Reduction (SCR)

SCR offers the benefit of sulfur-tolerant NO_x control at the expense of additional infrastructure requirements and emissions concerns. SCR catalysts utilize a nitrogen-containing compound such as urea or ammonia as a reductant in lieu of a hydrocarbon like diesel fuel. While the use of urea or ammonia avoids the fuel economy penalties associated with using fuel as a reductant, it also carries its own drawbacks. A new infrastructure for distributing the reductant would be required, as would a refueling system for diesel fuel and urea acceptable to consumers. The addition of nitrogen-based reductants also introduces new health concerns such as "ammonia slip," the release of unreacted ammonia during transient (non-steady-state) operation.

SCR is a common technology in stationary applications with steady-state operation (such as power plants). In Europe, it is regarded as a potential NO_x control technology for vehicles, driven by the centralized fueling there of heavy trucks, which can also use the technology. SCR is viewed with less optimism in the United States. Currently, Ford is the only automaker publicly pursuing SCR as a domestic NO_x control technology, as demonstrated by its diesel Focus prototype.

Integrated After-Treatment Devices

The future of after-treatment may well involve "integrated" devices that combine, for example, a NO_x adsorber and diesel particulate filter into a single component. Initial tests of integrated after-treatment systems look promising, with most systems aiming at reaching either proposed EURO V targets with passenger cars or Tier 2, bin 5 levels with SUVs, while maintaining modest fuel penalties in each (T.V. Johnson 2003).

Toyota's integrated Diesel Particulate-NO_x Reduction (DPNR) after-treatment system has proved capable of reducing both NO_x and PM by more than 80 percent when using a fresh catalyst. Appropriate temperature control in the system is a critical issue, however, as greater amounts of trapped PM have been shown to limit the device's ability to oxidize particulates (Nakatani et al. 2002).

Fuel Quality

Lowering the sulfur content of fuel is of equal importance to engine and after-treatment controls in reducing emissions from diesel passenger vehicles. Sulfur in diesel fuel has been shown to contribute to the generation of pollutants during the combustion process (T.V. Johnson 2002a). Moreover, just as sulfur poisons conventional three-way catalysts in gasoline vehicles, it inhibits the performance of NO_x and PM after-treatment devices on diesel vehicles. Because of these negative impacts, the level of sulfur in diesel fuel has become a linchpin in the near-term viability of diesel passenger vehicles in the United States. Consequently, both the federal government and California have mandated the use of ultra-low-sulfur diesel fuel beginning in 2006.

Sulfur Effects on After-Treatment

The negative effects of sulfur on after-treatment devices are numerous. Sulfur contributes to the congestion of particulate filter pores and damages lean-NO_x catalysts. On a chemical level, sulfur oxides (SO_x) in the engine exhaust compete for active NO_x adsorption and precious metal sites in NO_x adsorbers. SO_x combines with precious metals at the adsorber sites, forming thermodynamically stable compounds that require very high temperatures for removal. Lack of active sites hampers operation of the catalyst, yielding higher tailpipe pollutant levels.

A few advanced after-treatment approaches, such as plasma-assisted catalysis and selective catalytic reduction, are fairly tolerant of sulfur in diesel fuel. However, other technological and practical hurdles prohibit these approaches from making significant inroads as vehicle emissions-control devices at present.

Refining Issues

The desulfurization of fuel requires heating and pressurizing oil, injecting hydrogen into the oil in the presence of a catalyst, and removing the sulfur from the fuel. Further sulfur reduction requires higher pressures and temperatures, better catalysts, and higher-purity hydrogen (Yacobucci et al. 2001). This process adds to the cost and energy requirements of diesel fuel production, reducing some of the benefit diesel has had by virtue of being a less refined product than gasoline.

Biodiesel

Although this report does not focus on alternative diesel fuels, a brief discussion of biodiesel is warranted. Biodiesel is a petroleum-free fuel, typically produced from vegetable oils or animal fats. It may require fossil fuel, however; methanol from natural gas is often used in converting the fats and oils to fuel. Pure biodiesel (B100) is rarely used in vehicles, but use at lower levels, as in B20 (20 percent biodiesel, 80 percent conventional diesel), yields a reduction in hydrocarbon emissions, PM, and carbon monoxide compared to conventional diesel. Little or no engine modification is required. The reductions in these pollutants are modest, however, due to the limited biodiesel content of B20. Furthermore, the use of biodiesel (in both B20 and B100 form) yields a slight increase in NO_x emissions compared to conventional diesel (NBB No date-a). Biodiesel advocates argue that the low sulfur content of biodiesel permits the use of after-treatment devices to control NO_x emissions. However, continued after-treatment challenges even using ultra-low-sulfur diesel raise questions of biodiesel's viability as a comprehensively clean alternative.

Current cost and production capacity numbers indicate that biodiesel is not a broad solution to cleaning up diesel vehicles. One recent average wholesale price comparison placed biodiesel as 42–95 percent more expensive than conventional diesel, with variability depending on the biodiesel feedstock source (Yacobucci 2001). Not surprisingly, usage is currently limited. In 2001, approximately 25 million gallons of biodiesel were consumed in the United States, roughly 0.07 percent of the amount of diesel fuel consumed (Yacobucci 2001). Biodiesel advocates estimate current dedicated production capacity at 60–80 million gallons per year, with longer-term potential of approximately 400 million gallons (when considering available capacity in the oleochemical industry) (NBB No date-b). However, even at this higher level, biodiesel would only supplant 1 percent of diesel consumed in the United States today.

MARKET PROSPECTS

In addition to dramatically reducing tailpipe pollution, diesel vehicle manufacturers must address the cost and consumer acceptance issues described above. Progress on these fronts is mixed.

Cost

To bring diesels back into the US light duty market, automakers must make a business case for them. In particular, they will need to bring diesels' higher prices in line with the benefit from the purchaser's perspective.

Previous analyses assess the importance of upfront and operating costs in new car purchasing decisions (Truett and Hu 1997). Research indicates that the role of fuel economy in consumers' purchase decisions is limited to fuel-savings payback over the first few years. While the efficiency advantage of diesel vehicles is substantial, the low cost of fuel and the relatively small price differential between diesel fuel and gasoline make full payback in that timeframe difficult today. Furthermore, with the additional expense of emissions-control equipment to meet Tier 2 requirements, it is likely that the price differential between comparable gasoline and diesel models will grow. Cost estimates for Tier 2-based emissions-control systems have not been publicly declared, however, and shifting profit margins may mask the true costs of these technologies.

A comparison of the price premium for diesels available today (Table 2 above) and the fuel savings they offer is instructive. As shown in Table 4 below, the payback period of the diesel Jetta's price premium is 4–8 years, depending on transmission type and trimline. For the MDPVs, fuel economies are not available, as these vehicles are not subject to fuel economy standards; but reasonable estimates can be made. A medium-duty truck offering a 40 percent fuel economy improvement over a comparable gasoline version yields a $4,000 payback in approximately 12 years. A more aggressive 60 percent fuel economy improvement estimation provides a $4,000 payback in 9 years, and a $6,000 payback in 15 years.

Table 4: Estimated Fuel Savings Payback Periods for Sample Vehicles[1]

Model	Incremental Price	Gasoline Fuel Economy[2]	Diesel Fuel Economy[2]	Payback Period
MDPV[3] (40% improvement)	$4,000–$6,000	13.6 mpg	19.0 mpg	12–25 years
MDPV[3] (60% improvement)	$4,000–$6,000	13.6 mpg	21.8 mpg	9–15 years
2003 VW Jetta (manual)	$1,180–$1,390[4]	27 mpg	45 mpg	4–5 years
2003 VW Jetta (auto)	$1,180–$1,700[4]	26 mpg	38 mpg	5–8 years

Notes:

1. Assuming 15,000 miles of annual travel, constant 2001 gasoline and diesel fuel prices (EIA 2003), and a 7 percent discount rate.
2. Fuel economy denotes combined city/highway estimates, downward-adjusted to reflect real-world performance (i.e., "adjusted combined" fuel economy).
3. Fuel economy for sample medium-duty gasoline trucks cited by DOE (2000). Percents noted here provide a range of fuel economy improvement, and do not reflect actual vehicles. Incremental costs for these vehicles are rounded from incremental costs of MDPVs currently on the market.
4. Base MSRP comparison between TDI and 2.0L gasoline versions of the Jetta GL and Jetta GLS. Range depends on trimline.

The higher cost of diesel-powered vehicles appears to be less of a concern to automakers in the case of trucks. Diesel passenger truck sales have tripled over the past decade and continue to grow, despite a $4,000 to $6,000 price differential over comparable gasoline models. While it could be expected that advanced emissions-control systems will drive the incremental costs of diesel passenger trucks even higher, their strong sales performance in the face of a substantial price differential indicates that factors aside from price (such as high-torque capacity or engine durability) play a greater role in the purchasing decisions of these vehicles' buyers.

Comparisons are sometimes drawn between diesel and hybrid-electric vehicles in terms of prospects in the United States passenger vehicle market. Both can provide large fuel economy benefits but cost substantially more than their conventional gasoline counterparts. In both cases, sustained increases in the price or price volatility of fuel or higher fuel economy standards could boost sales; in the absence of such changes, neither is likely to claim a large share of the market in the near future.

There are key differences between the market outlook for diesels and for hybrids, however. While both hybrids and diesels are intrinsically more expensive to produce than conventional gasoline vehicles, in the case of hybrids, some reduction in cost would follow from production increases. This is not likely in the case of diesels, which have already achieved economies of scale in Europe and which will incur extra emissions control costs with the phase-in of Tier 2. Furthermore, hybrids are some of the cleanest vehicles on the road, while diesels have far to go in this regard. Finally, hybrids can be seen as a transitional technology to the vehicles of the future, given the inevitable demand for ever-higher electrical content. The transitional role of diesel is less clear, and diesel vehicles are not efficient enough to be regarded as a long-term end in themselves. If diesels offering a fuel economy gain of 50 percent took over the light-duty market in the next 2 years, oil consumption would be on the rise again by 2011.

Combining these two technologies could yield a promising medium-term vehicle: the hybrid-electric diesel. A diesel hybrid could indeed achieve an impressive fuel economy and could be superior, in terms both of GHG production and cost, to fuel cell vehicles (Weiss et al. 2000). While no manufacturer has announced plans for a light-duty hybrid-electric diesel to date, FedEx Corporation has begun the process of replacing 30,000 of its delivery trucks with hybrid-electric vehicles. Prospects for diesel hybrids in the light-duty market are unclear, however, given that they combine two expensive technologies and have some overlap in their benefits, such as low-end torque.

Consumer Perception

There has been much progress in improving the aesthetic aspects of light-duty diesel vehicles. Noise, vibration, and visible exhaust in today's diesel passenger vehicles have been greatly reduced from the previous generation of diesel vehicles. Performance is also improving. Upcoming models, such as the 200 hp Mercedes-Benz E320 CDI, offer significant improvements over traditional diesel horsepower levels. Zero-to-sixty times, traditionally high in diesel vehicles, are decreasing. The E320, for example, achieves 0–60 mph in less than 6.9 seconds, a performance indicator the industry clearly hopes will impress the American public (O'Dell 2003).

Faced with the challenges of Tier 2, some diesel advocates have proposed a relaxation of emissions requirements to ensure diesel's rapid progress in the market. That scenario seems unlikely, however, for two reasons. First, backsliding in federal standards may cause more states to opt out of federal requirements and into California's even-more-stringent tailpipe regulations. Second, from a public relations standpoint, the "clean diesel" image automakers are cultivating will be tarnished if diesels require a weakening of clean air standards to establish themselves in the market.

THE EUROPEAN CONNECTION

Current enthusiasm for a new generation of light-duty diesels in the United States has been generated in large measure by the enormous inroads these vehicles have made in Europe in recent years. The minimal usage of diesel vehicles in the United States stands in stark contrast to their popularity in Europe. Diesels constituted only 0.3 percent of all light-duty vehicles sold in the United States in 2001 (Ward's Communications 2002), when they reached 36 percent of the Western European new car market (Wright and Weernink 2002). A comparison of the U.S. and European automotive climates reveals that economic considerations and, more recently, global warming concerns are the major explanatory factors.

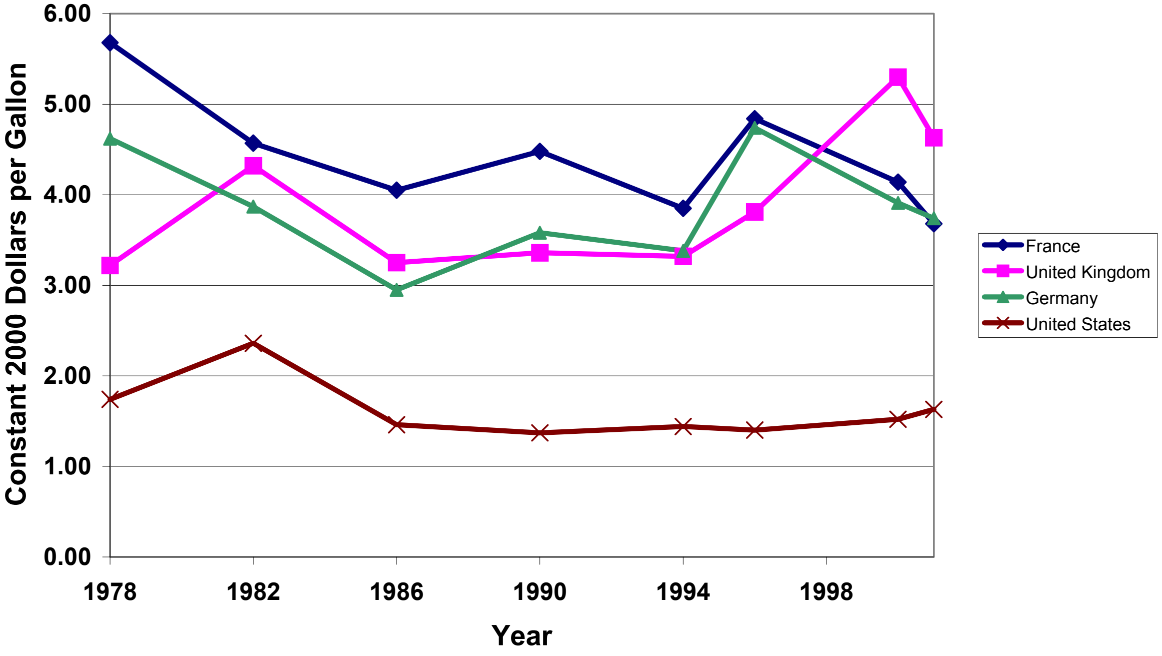
European and U.S. tailpipe emissions standards also differ significantly; the two systems are compared below. Models now appearing in Europe may not perform well by Tier 2 standards. These new models nonetheless provide a good indication of the state of emissions-control technology production, and we discuss a few significant examples at the end of this section.

Pricing Policies

In the United States, gasoline prices have hovered around $1.50 per gallon, with diesel generally slightly cheaper. Typical Western European gasoline prices range between U.S. $3.00 and $4.50 per gallon, while diesel prices lie around U.S. $2.50 to $3.00 per gallon (EIA 2002a; 2002b). This fuel price disparity between the United States and Europe has existed for decades, as shown in Figures 7 and 8, and is largely attributable to tax policy. In the United States, state and federal taxes together average only 37 cents per gallon for gasoline and 44 cents for diesel. The European Union, in contrast, taxes gasoline between U.S. $2.25 and $3.80 per gallon, and diesel in the range of U.S. $1.50 to $3.00 per gallon (Metschies 1999).

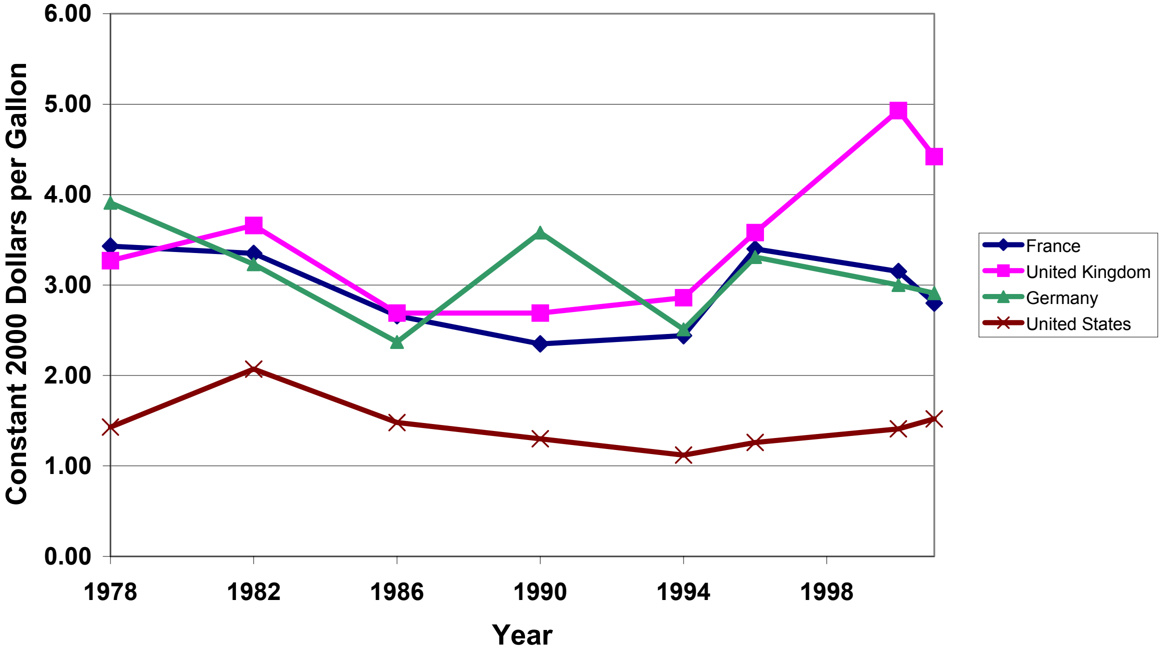
Thus diesel vehicles gain an advantage in two ways in Europe: high fuel prices provide a strong economic incentive for the purchase of fuel-efficient vehicles, and diesel fuel costs significantly less there than gasoline. Some E.U. members are eliminating the price differential between the two fuels (Schipper, Marie-Lilliu, and Fulton 2002), but increasing fuel economy is in the meantime becoming a higher policy priority. European governments have embraced diesel as a means of addressing global climate change and have implemented vehicle sales taxes and registration fees that encourage the purchase of more efficient vehicles. For example, Austria adopted a sales tax that results in significantly higher taxes for gasoline vehicles than for diesel vehicles (DTF 2001b).

Figure 7: Gasoline Prices for U.S. and Select European Countries, 1978-2001



Source: Davis and Diegel (2002)

Figure 8: Diesel Prices for U.S. and Select European Countries, 1978-2001



Source: Davis and Diegel (2002)

It is important to note that the shift to diesels has not produced nearly the reduction in fuel consumption that one would predict on the basis of model-by-model comparisons of diesel and gasoline fuel economy (Schipper, Marie-Lilliu, and Fulton 2002). Along with this shift have come changes in driving patterns and vehicle selection that mute the expected effect. While some of the important factors in this phenomenon are specific to Europe, others could be expected to apply in the United States as well.

Emissions Requirements

The European Union's EURO I emissions standards were adopted in 1992. Since then, the standards have tightened with the 1996 and 2000 phase-ins of EURO II and EURO III, respectively. Currently, auto companies are preparing vehicles for compliance with EURO IV, scheduled for introduction in 2005, while proposed EURO V targets are slated for 2008.

Comparing the U.S. and European standards is not straightforward. Differing certification protocols and test drive cycles preclude an "apples-to-apples" comparison (Kenney 1999). Additionally, the "useful life" durability requirement of Europe's existing EURO standards (80,000 km, or 49,712 miles) is significantly shorter than the 120,000-mile Tier 2 requirements set by EPA (based on Kenney 1999). Lastly, unlike Tier 2 standards, EURO standards set a strict upper bound for each pollutant. In spite of the difficulty of drawing comparisons between European and American emission standards, it generally agreed that U.S. Tier 2 NO_x and PM standards for light-duty diesels are more stringent than upcoming EURO IV standards. Arguments have been made, however, that the European driving cycle is more taxing for diesels in that low exhaust temperatures retard the start of catalyst operation (Friedrich 2003a). With these caveats, Table 5 below compares U.S. and E.U. emissions standard levels.

Table 5: Select E.U. and U.S. NO_x and PM Emission Standards for Diesel Passenger Cars

U.S. Standards	Year Introduced	NO_x (g/mi) 5 yr/50K mi	PM (g/mi) 5 yr/50K mi	NO_x (g/mi) 10 yr/120K mi	PM (g/mi) 10 yr/120K mi
Tier 1	1990	1.0	0.08	1.25[a]	0.10[a]
Tier 2, bin 10	2004	0.4	-	0.6	0.08
Tier 2, bin 9	2004	0.2	-	0.3	0.06
Tier 2, bin 8	2004	0.14	-	0.20	0.02
Tier 2, bin 5	2004	0.05	-	0.07	0.01

European Union Standards[b]	Year Introduced	NO_x (g/mi) 50K mi	PM (g/mi) 50K mi
EURO I	1992	-	0.29
EURO II	1996	-	0.13[c]
EURO III	2000	0.81	0.08
EURO IV	2005	0.40	0.04
EURO V[d]	2008	0.13	0.004

Sources: Federal Register (2000); Friedrich (2003b)

[a] Tier 1 useful-life standards are 10 year, 100,000 mile.

[b] Standards converted from g/km to g/mi.

[c] Standard for direct-injection engines prior to 1999 was 0.16 g/mi.

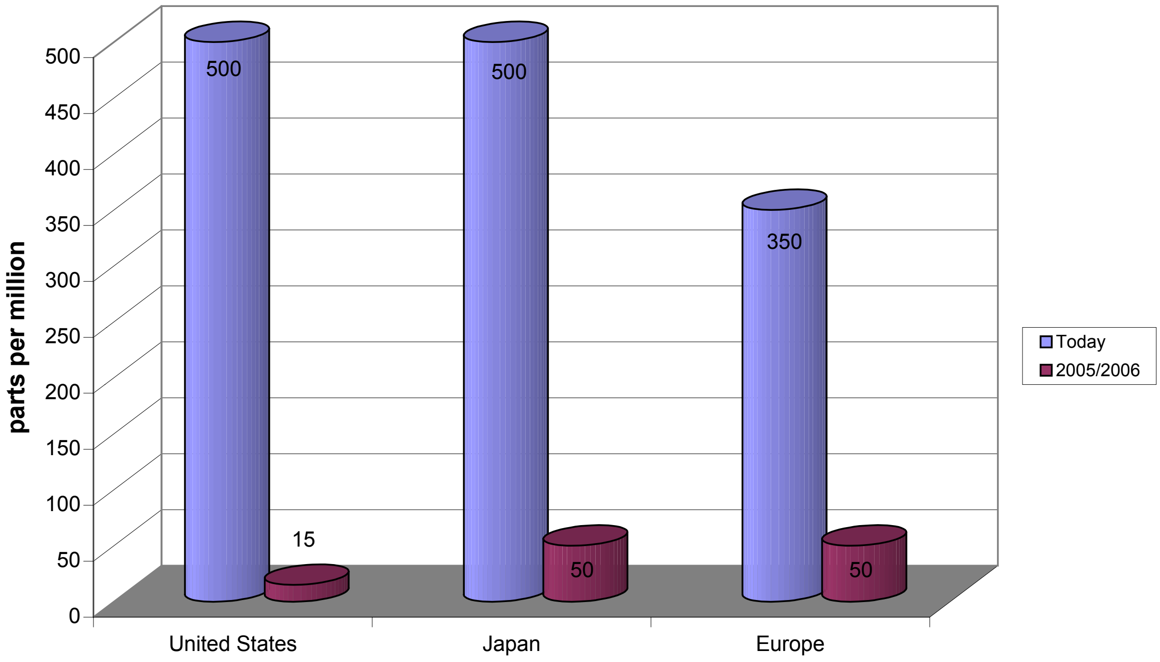
[d] Proposed standards.

Noteworthy European Models

Because of the popularity and prominence of diesel vehicles in Europe, one can look to that market for a snapshot of production-ready emissions-control devices. European diesel sulfur levels are currently lower than those found in the United States, however, so certain after-treatment technologies seeing European use may be unable to operate properly in the United States at this time. As shown in Figure 9, sulfur levels are set to change both in the United States and abroad over the next few years.

Peugeot's *607* diesel luxury sedan won European acclaim in early 2000 as the first modern particulate filter-equipped passenger car. It achieved low NO_x levels of 0.06 g/mi as well, despite the high sulfur levels found in diesel in France, under the European test protocol. Filters were used on early 1980s diesels in Germany, but they were quick to clog with soot and were subsequently discontinued. The modern filter system, supplied by Faurecia, burns excess soot from the filter by increasing the engine exhaust temperature. This regeneration process takes approximately 3 minutes and is automatically performed every 250–300 miles (DTF 2001b). The filter, which works in conjunction with a common-rail fuel injection engine system, will soon be added to Peugeot's popular *307* model. A less expensive, second-generation filter is currently in development. Approximately 270,000 cars were expected to be equipped with diesel particulate filters in 2002 (Wright and Weernink 2002).

Figure 9: U.S., Japanese, and European Diesel Sulfur Standards



Source: Crain (2003)

General Motors Europe recently announced a EURO IV-compliant diesel particulate filter system which will be introduced on its Opel/Vauxhall Vectra and Signum lines. Placed on models with the 1.9-liter CDTi Ecotec diesel engine, the emissions control system includes a precatalyst (placed near the engine), an oxidation catalyst, and a precious metal-coated silicon carbide particulate filter. Post injections from the vehicle's common rail system will accommodate filter regeneration, avoiding the need for fuel additives as required in Peugeot's *607* (Vauxhall 2003).

In March 2002, Toyota began a monitoring program to assess its Diesel Particulate NO_x Reduction (DPNR) emissions-control system under real-world conditions. The 1.5-year program will evaluate sixty of Toyota's 2-liter, 4-cylinder diesel Avensis sedans in seven European countries. The evaluation is seen as a step forward in Toyota's planned introduction of a DPNR-equipped model by 2003 (DieselNet 2002).

The DPNR system is a public example of an integrated NO_x/PM control device, and is the first commercial application of a NO_x adsorber on a diesel vehicle (EPA 2002b). Essentially a particulate filter with a NO_x adsorber catalyst coating on the filter walls, the integrated device simultaneously and continuously traps and reduces particulates and nitrogen oxides. The DPNR system on the Avensis works in conjunction with Toyota's common-rail, direct-injection D-4D diesel engine (DieselNet 2002).

In March 2002, EPA tested the DPNR-equipped Avensis (comparable to those tested in Europe) at its vehicle testing facilities in Ann Arbor, Michigan. While the vehicle was not optimized for U.S. driving cycles, results of the tests are promising. Tested over the basic federal test procedure (FTP75) cycle, the Avensis was capable of meeting the bin 5 intermediate-life (50,000-mile) NO_x emission standard of 0.05 g/mi. The vehicle should not, however, be considered Tier 2-compliant. The high-powered driving test (US06) results of 0.14 g/mi NO_x and 0.19 g/mi NMHC (non-methane hydrocarbon) far exceeded the 4,000-mile supplemental federal test procedure (SFTP) requirement of NO_x + NMHC = 0.14 g/mi. Neither the SC03 air conditioning test nor any high-mileage tests appear to have been performed on the vehicle. One would expect emissions-control system degradation, more diverse driving conditions, and sulfur variability in real-world usage to increase vehicle emissions.

THE AMERICAN MARKET

Three car models, all from Volkswagen, are the extent of light-duty diesel offerings in the United States today. The remainder of diesel passenger vehicles available at present are medium-duty passenger vehicles (also known as "Class 2b" trucks), i.e. those between 8,500 and 10,000 lbs. GVW. Although diesel MDPVs are currently available in only a handful of nameplates, annual sales of these trucks approach a half-million—about one-third of the MDPV market (Davis and Diegel 2002; Davis and Truett 2002). The predominance of MDPVs among diesels is presumably in large part a result of diesel durability and high torque, characteristics seen as appealing in these largest of passenger vehicles. In contrast, the light truck market today is dominated by upscale, midsize SUVs with little need for such capabilities.

Noteworthy North American Models

VW's three TDI models are popular among diesel enthusiasts but currently account for only 9 percent of Volkswagen's total U.S. sales (Groth 2002). However, Volkswagen has seen rapid growth in their U.S. diesel sales over the past few years. In the last 5 years, sales increased eightfold, from roughly 4,000 vehicles in 1997 to more than 33,000 vehicles in 2002 (Groth 2002).

In early 2003, Ford introduced the 6.0L Power Stroke diesel engine, to replace eventually the 7.3L Power Stroke diesel engine available on Ford's Excursion SUV and F-Series Super Duty pickup truck models. Capable of producing greater peak horsepower and torque than its predecessor, the new engine allegedly offers an 8 percent improvement in fuel economy and a 20 percent reduction of NO_x emissions relative to the 7.3L engine. Notable features on the new 32-valve engine include a variable nozzle turbocharger and a cooled exhaust gas recirculation (EGR) system.

The initial release of the vaunted 6.0L Power Stroke was marred by complaints of vehicle bucking and stalling in cold weather, later tracked to a defective injection control pressure sensor. In the spring of 2003, Ford recalled for repairs all affected vehicles, which the company estimates at 67,000. Ford anticipates annual sales of over 200,000 trucks with the 6.0L Power Stroke, about 40,000 more than with the previous 7.3L engine (Wilson 2003).

Upcoming U.S. Models

Information on upcoming diesel models in the United States is sparse at this time. Although a number of automakers seem eager to bring advanced diesels to market in this country, few have disclosed detailed product plans. Those that have subsequently have announced project delays, lending an air of uncertainty to this market's reemergence.

Ford

Ford had planned to break new ground in the diesel market by offering a 4.5L V6 version of its Power Stroke diesel engine on its F-150 pickup, Expedition/Navigator SUV, and E-150 Van—possibly as early as model year 2005 (Truett 2002). However, in October 2002, Ford abruptly cancelled plans to use the new engine, prompting a lawsuit from engine manufacturer Navistar/International, who had already begun pre-production of the new diesel engine. In April 2003, Ford and Navistar settled their dispute with an undisclosed Ford payout.

The 4.5L engine for the F-150 would have been Ford's first diesel foray into the light-duty truck segment since its diesel Ranger pickup in the late 1980s. Unlike the current diesel trucks available in the US now, which exceed 8500 pounds GVW, a diesel version of the immensely popular F-150 could play a significant role in Ford's light truck corporate average fuel economy (CAFE), allowing the company to lower the fuel economies of its gasoline trucks while remaining CAFE-compliant.

Despite shelving plans for the diesel F-150, Ford clearly has not abandoned its light-duty diesel efforts. In mid-2003, Ford announced the formation of its North American Diesel Team, a group of more than fifty of its top diesel engineers, selected to develop car and light truck diesel engines capable of meeting Tier 2 emission and durability requirements (Truett 2003c).

In July 2002, Ford announced it was considering producing a diesel-powered version of the popular Focus compact car in the United States "within the next five years" (Ford Motor Company 2002a). At the time of the announcement, Ford claimed it would only bring the diesel Focus to market if it could meet the upcoming Tier 2 emissions standards, and that low-sulfur diesel fuel (15 ppm or less) would be necessary to meet those standards. Because low-sulfur fuel is not required until late 2006, it is reasonable to expect that a diesel Focus would not be available in the United States before the 2007 model year. The Focus would therefore need to achieve at least a bin 8 certification, as higher bins are phased out for passenger vehicles after the 2006 model year.

One of the after-treatment strategies Ford is investigating to control NO_x emissions in the Focus is selective catalytic reduction. This seems a risky undertaking, since, as discussed above, it would require infrastructure for urea that could become obsolete should another technology prove to yield better NO_x control.

DaimlerChrysler

DaimlerChrysler is planning to release diesel models in the United States from both Chrysler Group and Mercedes-Benz. The Jeep Liberty, a compact SUV, will receive an optional 2.8L common-rail turbodiesel engine, and will be available in both two- and four-wheel drive versions. The Liberty's microprocessor-controlled pilot and/or multiple fuel injections will lower combustion temperatures and NO_x emissions as well as minimize engine knock, a trait associated with earlier diesels (Cogan 2003).

Chrysler projects the initial, model year 2005 production run of the diesel Liberty at 5,000 units but has stated that Jeep will not cap production if consumer demand exceeds that number (Truett 2003a). The tenure of the diesel Liberty is unclear, however, because it will be certified to either bin 9 or bin 10, both of which are unavailable to trucks of this weight after model year 2006 (Truett 2003b).

The new Mercedes will be the brand's first light-duty diesel in the U.S. market since model year 1999. Available in late 2004 or early 2005, the Mercedes-Benz E320 CDI (Common rail Diesel Injection) sedan will contain a 6-cylinder turbocharged diesel currently used in European models. The U.S. version is rated at 200 hp and 370 lb-ft. of torque, with a top speed of 130 mph and estimated fuel economy of 35 mpg. Prices for the diesel model are expected to begin at $50,000. The gasoline V6-powered E320 averages 25 mpg, with 221 hp and 232 lb-ft., and a starting price of $47,000 (Henry 2003; O'Dell 2003; Truett 2003b).

Volkswagen

Volkswagen will expand its U.S. diesel offerings over the next few years. VW has announced plans to release diesel versions of the Passat sedan in late 2003, Touareg SUV in mid-2004, and Phaeton luxury sedan at an unannounced later date. These vehicles will receive engines not used previously U.S. Volkswagens. The Passat will be powered by a 134 hp, 2.0L, 4-cylinder engine using the latest version of VW's TDI system, while the diesel versions of both the Touareg and Phaeton will use a new 5.0L V10 diesel engine (Kisiel 2003a; Ostle 2003).

Projected sales of the Passat and Phaeton have not been announced, but sales of the diesel Touareg are expected to be approximately 6,000 units annually. This amounts to about 15 percent of all Touaregs sold. Volkswagen has stated that the model will be compliant with Tier 2 bin 9 or 10, but it is still unclear whether it will be able to meet more stringent standards effective in 2007 (bin 8 or better). Gasoline models in the United States will be priced between $35,000 and $41,000 (Kisiel 2003b). Prices on the diesel version have not been set for the U.S. market, although the diesel version in Europe costs 65 percent (27,000 Euros) more than the gasoline version (Resch 2003).

During interviews conducted for this report, Volkswagen indicated its intention to produce a diesel passenger car that emits at most 0.07 g/mi of NO_x, in order to avoid putting an emissions constraint on the rest of its fleet (S. Johnson 2002).

CONCLUSION

Diesel vehicles could offer an important opportunity to increase the fuel economy of U.S. passenger vehicles, but significant questions remain unanswered.

Feasibility

Diesels clean enough to meet upcoming emissions standards are technologically feasible, assuming fuel sulfur levels decline as they are required to do. Elimination of other historical performance drawbacks of diesels appears to be imminent. Unresolved issues about the feasibility of a major diesel presence in the U.S. passenger vehicle market are therefore reduced to: (1) the timeframe for manufacture of these new, cleaner diesels, which will determine whether emissions regulations affect the rate of diesels' market penetration over the next decade; (2) how rapidly other cost-effective advanced technologies enter the market; and (3) the cost of clean diesel vehicles relative to gasoline vehicles, and whether their performance is sufficiently attractive to U.S. buyers to outweigh that higher cost.

Timing

It is likely that manufacturers can continue to put some diesel products on the market in the early days of Tier 2. Cars falling into bins 7 or 8 for the next 3 years, followed by some as clean as bin 5 with the advent of ultra-low-sulfur diesel in late 2006, are likely to materialize. Production of diesel trucks in the 8,500 to 10,000 lbs. GVW range can be expected to continue in the near term, given the less stringent Tier 2 requirements for this weight class during the phase-in period.

On the other hand, the biggest new market opportunity for diesels is probably among the heavier light trucks (6,001 to 8,500 lbs. GVW), where no vehicle close to production appears primed to meet bin 5 standards in the near future. Light trucks may be developed to meet interim bin requirements in the first few years of the program, but will need to meet bin 8 shortly thereafter. Within one product cycle, it will be impossible to produce vehicles in bins higher than bin 5 in large volume, unless manufacturers have enough very low bin vehicles to offset them. With the advent of ultra-low-sulfur fuel, the goal of bin 5 should be achievable for light trucks, though exact timing is difficult to predict.

Competition

Diesel's success as a competitor to the full range of advanced technologies will be determined by a host of factors, including automakers' current strategic decisions. Hybrids offer far better emissions performance and somewhat better fuel economy, though at a greater incremental cost. Should the upcoming hybrid SUV and pickup releases over the next few years prove successful, manufacturers may devote more of their resources to hybrid development. This will be especially true if no role for diesel emerges in longer-term plans for advanced vehicle development.

Cost and Market Appeal

There is no strong evidence that even very clean diesels will make major inroads in the U.S. car market absent a significant increase in petroleum prices or fuel economy standards. The light truck market, where current fuel economy standards may be more of a factor in manufacturers' choice of product offering, could present greater opportunities. In light of the rapid growth in diesel's share of the medium-duty passenger vehicle market, there could be substantial demand for these smaller diesel trucks as well, if they were to be made available. On the other hand, it remains to be seen whether the durability, fuel economy, and towing capacity advantages of diesels are sufficient to attract buyers of these smaller SUVs and pickups, given the high cost differential between diesel and gasoline trucks.

Societal Benefit

Various factors coming into play will erode to some degree the energy advantage of diesel over gasoline vehicles: the efficiency penalties of certain emissions-control technologies; the improvement of gasoline vehicle technologies; and the increased processing required for ultra-low-sulfur diesel, for example. But despite these factors, diesels' intrinsic efficiency advantage will continue to be large. Assuming that the feasibility issues above can be resolved in diesel's favor, a shift to diesel in the light-duty sector remains an important option for reducing petroleum consumption and greenhouse gas emissions. Other issues must be considered in deciding whether diesel is a prudent approach, however.

Serious environmental concerns persist, even with Tier 2 regulations in place. Higher bins that accommodate diesel vehicles in the interim period will allow greater numbers of diesels on the road with less mature emissions-control technologies. As noted above, even when the Tier 2 phase-in is complete, sales of diesel vehicles in the higher bins will result in higher total PM emissions, despite the existence of fleet-averaging requirements for NO_x.

The fact that nanoparticles and various air toxics associated with diesels are not regulated remains an issue as well. These pollutants are closely tied to regulated pollutants, but health impacts specific to ultrafine particles and individual air toxics are not adequately addressed by standards in place. The efficacy of particulate filters in eliminating nanoparticles will remain an important issue, even when they can deliver Tier 2 compliance, because achieving very low grams per mile emissions of fine particles as a whole does not ensure any reduction in the emissions of the smallest particles. Further research may find additional tailpipe regulation to be warranted, which could once again pose greater problems for diesel than gasoline vehicles.

Furthermore, in the absence of policies to raise fuel economy, an increase in diesel sales is unlikely to reduce fuel consumption, as recent history has demonstrated in the case of other efficiency technologies. For the past 15 years, manufacturers have coupled efficiency enhancements with more easily marketed attribute changes that reduce efficiency, resulting in no net gain in fuel economy. Manufacturers are particularly interested in ways to increase performance of their heavier light trucks without exceeding CAFE limits. Even in Europe, the arrival of diesels has not produced substantial fuel savings, due in part to accompanying changes in vehicle purchase and driving patterns.

Finally, there is the question of whether diesel has a role in the path for advanced vehicle technologies in the long term. While it is hard to predict the rate at which new technologies will become established in the market, one can assume that very efficient and low-polluting vehicles will arrive. Hybrids in this sense have a more obvious tie to the future of the automobile than does diesel, in that the increasing electrification of vehicle component systems is inevitable.

Policy Implications

Caution should be exercised in proposing policy measures to increase the presence of light-duty diesel in the U.S. market. To begin, no further concessions to diesels in tailpipe standards are warranted. In neither niche established to date (medium-duty passenger vehicles and a small segment of the compact car market) do Tier 2 standards seem to pose a real threat to diesel development. That diesel emissions are a serious public health threat is well established, and trading the health benefits of Tier 2 for the potential energy savings of diesel is counterproductive. There are many technologies currently available to improve the fuel economy of gasoline vehicles, and these should rank higher as technologies to promote until diesel vehicles are equally clean.

Second, there is not a good argument for offering tax incentives for diesels over other technologies to improve vehicle efficiency. Among such technologies, direct-injection diesel is certainly one of the better established, as the current European market reveals. Support for advanced emissions-control systems for diesel may be warranted, but any incentive offered for advanced emissions technology should certainly require superior performance (better than

Tier 2 bin 5) at a minimum and should be pegged to the cost and efficacy of emissions control. More generally, such tax incentives should be designed to fit into a comprehensive, technology-neutral strategy to improve the environmental performance of new vehicles.

Proposals have been made to accelerate mandatory production of ultra-low-sulfur diesel or to further lower its sulfur content to less than 15 ppm. It is unlikely that industry-wide production of ultra-low-sulfur diesel production can be significantly accelerated at this point. Incentives to achieve 15 ppm early could be beneficial, but it should be recognized that after-treatment systems with low sulfur tolerance cannot be widely implemented until ultra-low-sulfur diesel is universally available. Given manufacturers' statements that 15 ppm sulfur fuel is not clean enough to ensure Tier 2 compliance for the diesels they seek to produce, there may be some merit in continuing investigation into lowest practical sulfur levels and their effects on emissions, cost and fuel economy.

A further policy issue is the allocation of federal funds for research and development of light-duty diesel vehicles. This is worthwhile in principle, though, as in the case of tax incentives, the federal government should allocate research dollars to advancing emissions reduction and petroleum savings, not to helping manufacturers scrape by Tier 2 and fuel economy standards. Thus, for example, an emissions level target of at least bin 5 should be adopted by the 21st Century Truck program as a condition of continued funding. Moreover, such programs should not be regarded as substitutes for an aggressive fuel economy program.

When diesel vehicles are as clean as gasoline vehicles, U.S. consumers will have a clear choice to make: whether diesels' fuel savings and performance advantages are enough to offset their higher purchase price.

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