Demand for Diesels:

The European Experience

Harnessing Diesel Innovation For Passenger Vehicle Fuel Efficiency and Emissions Objectives

Diesel Technology Forum
www.dieselforum.org

Foreword

With major European and American auto manufacturers already planning diesel introductions of popular models into the U.S. market as early as 2004, many predict that diesel is poised to make a comeback in the United States, thanks to new, clean diesel technologies.

This paper – Demand for Diesels: The European Experience is the Diesel Technology Forum's analysis of the role of diesel technology in Europe, and why advanced modern diesel cars, pickups and SUVs (sport-utility vehicles) hold such great promise for helping the United States achieve its energy and environmental goals.

The Diesel Technology Forum represents manufacturers of engines, fuel and emissions control systems. It brings together the diesel industry, the broad diesel user community, civic and public interest leaders, government regulators, academics, scientists, the petroleum industry and public health researches to encourage the exchange of information, ideas, scientific findings and points-of-view to current and future uses of diesel power technology.

For more information about the Forum and to download this and other information, visit our web site at www.dieselforum.org.

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July 2001

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EXECUTIVE SUMMARY

Diesel automobiles are extremely popular in Europe, and demand continues to grow. One in every three cars sold in Europe today is powered by a diesel engine. Experts predict that diesels will soon gain about 40% of the European market. There are several reasons why diesel cars have won such approval in Europe:

- *Inherent Performance Advantages of Diesel*. Europeans have found that light-duty diesel vehicles – cars and small trucks – offer significant inherent performance advantages over gasoline-powered vehicles. These include:

  - *Better Fuel Efficiency*. Light-duty diesels use 30-60% less fuel than gasoline engines of similar power. Some of the most advanced models are attaining astonishing fuel efficiency, such as the European-market Audi A2 that achieves 87 mpg on the highway.

  - *More Power*. Diesels produce more drive force at lower engine speeds than gasoline engines.

  - *More Durability*. A typical light-duty diesel engine is built to last well over 200,000 miles. Diesel engines also require less maintenance and have longer recommended service intervals than gasoline engines.

  - *Fewer Greenhouse Gas Emissions*. Because diesels burn less fuel than gasoline vehicles, they also produce significantly lower emissions of greenhouse gases such as carbon dioxide.

- *Clean and Quiet Technology*. Use of the latest diesel technology has nearly eliminated the noise and smoke that many Americans remember from early diesel cars. With the application of advanced technologies such as direct injection lean-burn combustion, particulate traps and catalytic converters, diesel vehicles are now a clean and quiet alternative to less efficient gasoline powered cars.

- *European Tax Incentives*. European governments encourage the use of diesel technology to reduce greenhouse gas emissions and to limit reliance on foreign oil. Fuel tax structures make diesel fuel cheaper than gasoline, and vehicle sales taxes encourage the purchase of diesel technology.

- *European Emissions Standards.* European emissions regulations are designed aggressively to reduce diesel emissions such as nitrogen oxides (NOx) and particulate matter (PM), but are structured to maintain the market viability of diesel vehicles as emission reduction technology advances. This approach takes full advantage of diesel's inherently low emissions of carbon monoxide, hydrocarbons, and carbon dioxide.

In contrast to Europe, the light-duty diesel market in the United States is practically nonexistent. Although extensive U.S. research and development – like the Partnership for a New Generation of Vehicles – has demonstrated the substantial fuel efficiency advantages that diesel technology can bring to the domestic market, the upcoming Tier 2 regulations establish emissions levels that constitute a significant challenge for the future of diesel vehicles in America. Consequently, most automakers – American and European – are not planning to offer more diesel technology in the United States. This denies American consumers the opportunity to experience the performance advantages and fuel savings of new diesel technology, and denies the nation the opportunity to reduce greenhouse gas emissions and limit dependence on foreign oil.

Demand for Diesels:
The European Experience

I. INTRODUCTION—A DIESEL DICHOTOMY

One-third of all new cars sold in Europe are diesel powered, and that number is climbing. European consumers flock to new advanced-technology diesel to get better fuel efficiency, more power, and more durability. Governments and some environmental groups encourage the trend, which reduces fuel consumption and greenhouse gas emissions.

But Americans don't have that option. The clean, quiet and powerful diesel cars that have captured a third of the European market are not available in the United States. The diesel Audi A2 delivers 87 miles per gallon on the highway, but is not sold in America.[1] The divergence in the American and European markets can be explained by a number of factors. Europeans have found that diesel cars achieve better fuel efficiency than gasoline cars without sacrificing performance. Fuel efficiency is an important factor for European car-buyers because of the increased cost of fuel in Europe. The economic advantages of driving a diesel car in Europe are heightened by governmental tax structures that favor diesel technology. In addition to such market-based factors, however, the divergence in diesel penetration is due in part to the different regulatory schemes employed in Europe and the U.S. to limit automobile emissions.

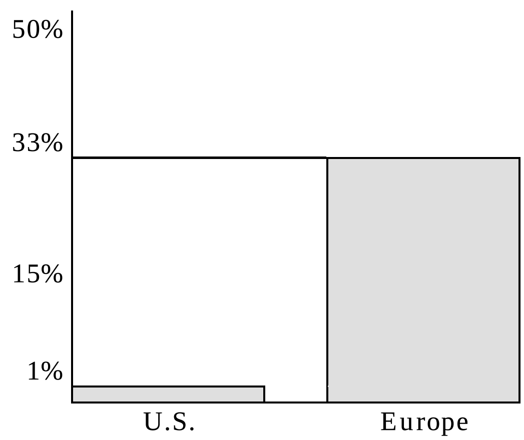
The European Union has adopted stringent diesel emission standards that encourage further development of advanced diesel technology, thereby ensuring that diesel engines will have low NOx and particulate emissions while taking full advantage of the diesel engine's naturally low emissions of carbon dioxide (CO_2). The United States, in contrast, adopted a new regulatory scheme that creates significant challenges to the use of diesel technology. Car manufacturers know ahead of time that they will have difficulty producing affordable diesel vehicles that meet the new U.S. Tier 2 standards. Consequently, there are few plans to develop diesel technologies for the U.S. market. Not only could the American consumer be denied the opportunity to experience advanced diesel performance and fuel economy savings, but the United States will also miss the opportunity to achieve dramatic, cost-effective greenhouse gas reductions.

This paper documents the significant strides in diesel technology that have won widespread acceptance in Europe, and contrasts European policies with the U.S. regulations.

II. RAPID GROWTH OF THE EUROPEAN LIGHT-DUTY DIESEL MARKET

The U.S. market for light-duty diesel vehicles is practically nonexistent. In the year 2000, diesel passenger cars accounted for 0.26% of all new cars sold in America.[2] In western Europe, by contrast, light-duty diesels currently capture about 33% of total new car sales.[3] See Figure 1.

Figure 1: Comparison of U.S. and E.U. Diesel Market Share



While the U.S. light-duty diesel market shows no sign of growth, the popularity of diesels in Europe has grown significantly over the past few years, with no sign of slowing down. Diesel car purchases have grown from 14% of the European market in 1990[4] to about 22% in 1995.[5] By 1999, the market share was more than 28%, and today it is about 33% of total new car sales.[6] European auto-manufacturers expect that overall European diesel penetration will soon climb to about 40% of the market, and may even approach 50% within 10 years.[7]

The popularity of diesels is already even greater in some countries. In 1999, diesels claimed 61% of the market in Austria, 54% in Belgium, and more than 50% in France.[8] France claimed the highest annual number of diesel car sales in Europe, registering close to 1 million new light-duty diesels in 1999.[9]

Americans may be surprised to learn that trend-setting luxury car buyers are demanding the most diesel technology. Recent research shows that 44% of all luxury cars purchased in Europe are powered by diesel engines.[10] Diesel sales make up 87% of the premium segment in Belgium, 82% in France, 77% in Austria, and 70% in Italy.[11]

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III. THE ADVANTAGES OF HIGH-TECH DIESEL

Diesel sales continue to grow because European drivers have first-hand experience with the performance advantages of advanced clean diesel technology. Few Americans are aware of the recent technological advances that have markedly improved the engine's performance and reduced emissions. Today, most Americans' image of diesel cars is formed by memories of the outdated low-tech diesel cars of the 1970's, or the older smoking heavy-duty trucks or transit buses that still can be seen on the roads today. Nothing could be further from the public perception in Europe, where diesel power dominates the luxury vehicle market and is synonymous with the highest standards of performance and reliability.

A. Inherent Performance Advantages of Diesel

Diesels hold significant inherent performance advantages over gasoline engines in fuel efficiency, power, durability and certain emissions. Diesel's superiority in these areas has made it the overwhelming choice for most heavy-duty engine applications worldwide, including in the United States. The same performance characteristics that lie behind diesel's dominance in the heavy-duty sector lay the foundation for diesel's light-duty popularity in Europe.

- *Better Fuel Efficiency.* Light-duty diesels use 30-60% less fuel than gasoline engines of similar power, depending on the type of vehicle and driving conditions.[12] These advantages come from both the greater efficiency of compression ignition and the higher energy content of diesel fuel.

  Diesel's compression ignition process results in greater thermal efficiency – more of the fuel's energy is harnessed during combustion. This improves fuel efficiency. In contrast, gasoline engines are less fuel efficient because they burn fuel at lower temperatures under lower compression. Diesel's superior fuel efficiency is also a result of diesel fuel's higher energy content. A gallon of diesel fuel contains roughly 11% more energy than a gallon of gasoline.[13]

  When the superior combustion efficiency and fuel energy density of diesels are combined, the fuel efficiency advantage of diesel cars is staggering. The 2001 VW Jetta equipped with a modern turbocharged direct injection diesel engine gets more than 66% better fuel efficiency than the comparable gasoline powered Jetta.[14] And while diesels dominate the European luxury vehicle market, they are also the first choice for power in Europe's most fuel efficient vehicles. In June 2001, Audi introduced a new A2 model with an ultra-efficient 1.2 liter 3-cylinder turbo diesel that gets 87 MPG on the highway and 79 MPG City/Highway combined.[15] The A2 is much more fuel efficient than even the latest gasoline/electric hybrids sold in the U.S. The 4 passenger diesel A2 is 23% more fuel efficient than the 2 passenger Honda Insight, which is the most fuel efficient car sold in America with a combined City/Highway mileage of 64 mpg.[16] The diesel A2 is 64% more fuel efficient than the more comparable 4-passenger hybrid Toyota Prius, which gets combined city/highway mileage of 48 mpg. As discussed in more detail in Section V below, the use of diesel engines, rather than gasoline, in hybrid electric vehicles offers even greater potential for fuel efficiency.

- *More Power.* Diesels produce more drive force at lower engine speeds than gasoline engines. This superior drive force is the result of the diesel engine combustion process, known as "compression ignition." Compression ignition produces superior combustion force in the cylinder, which in turn provides more power or "torque."

  For example, the Volkswagen 1.9 liter TDI diesel used in the popular Jetta has a compression ratio of 19.5 to 1. The compression ratio of the comparable 2.0 liter gasoline powered Jetta is about half that, at 10 to 1. As a result, the 1.9 liter diesel TDI develops torque of 155 lbs.-ft. at only 1900 RPMs, whereas the 2.0 liter gasoline engine develops only 122 lbs.-ft. of torque at a much higher RPM of 2600.[17]

- *More durable.* Diesel engines are generally more durable than spark ignition engines. Light-duty diesel engines generally last well over 200,000 miles.[18] Maintenance intervals are also generally longer for diesels. For example, the manufacturer's recommended service interval for a diesel Audi is 50,000 km, while the recommendation for the company's gasoline engine is 30,000 km.

- *Environmental Advantages.* The environmental advantages of diesel engines are better appreciated in Europe than in America, perhaps due to greater concern about emissions of "greenhouse gases." Of the five major mobile source emissions: carbon monoxide (CO), hydrocarbon (HC), carbon dioxide (CO_2), nitrogen oxides (NOx), and particulate matter (PM), diesels have far superior performance regarding CO, HC and CO_2. In addition, diesel fuel produces almost no evaporative emissions, in contrast to gasoline powered vehicles. Although diesel engines still produce more NOx and PM than gasoline engines, today's advanced diesel technology has cut these emissions significantly. As discussed in more detail below, this technology is rapidly improving and will soon permit even more substantial NOx and PM reductions.

B. Improving Strengths and Eliminating Weaknesses: Continuous Improvement of Advanced Light-duty Technology

European light-duty diesel vehicles have improved diesel's inherent fuel efficiency and power while eliminating noise and smoke by using the same advanced technologies that have revolutionized the performance of heavy-duty diesels in the U.S. The latest advances in lean-burn combustion technology have improved efficiency and power; and advanced emissions control technologies have reduced certain tailpipe emissions.

1. Advanced Lean-burn Combustion Technology

A lean-burn internal combustion engine is an engine that operates at an air-to-fuel ratio higher than the level necessary for complete combustion of the fuel. This means that there is excess air in the air/fuel mixture. Although diesel engines always operate with excess air, advanced direct injection lean-burn engine technology has refined the diesel combustion process to significantly improve performance.

Advanced lean-burn operation has a number of distinct advantages. It can provide a 20% to 40% improvement in fuel efficiency compared with conventional diesel engine technology, and a 40% to 60% improvement compared to conventional gasoline engines. Gasoline/electric hybrid cars have made headlines for fuel efficiency in the United States, but, as discussed above, advanced lean-burn diesel technology in traditional direct drive vehicles can meet or exceed the fuel savings of the gasoline/electric hybrids without relying on hybridization. Advanced lean-burn combustion also enhances the diesel's environmental advantages by further reducing emissions of HC, CO, and CO_2. Compared with conventional diesels, the latest Peugeot direct injection engine reduces CO by 20%, CO_2 by 20%, HC by 40%, PM by 60% (without the particulate filter system discussed below), and ozone precursors by 50%.[19]

The turbocharged direct-injection diesel engines in European passenger vehicles use sophisticated computer controlled technology to optimize the lean-burn process for greater fuel efficiency and emissions control. These engines directly inject fuel into the combustion chamber rather than combusting part of the fuel in a pre-chamber (indirect injection). Direct injection eliminates heat loss that robs the engine of efficiency. Optimized engine control through common rail fuel injection also tempers the combustion process, making engine operation smoother and more quiet. Advanced fuel injection systems pre-inject fuel before the main injection to cushion the impact of the sudden temperature and pressure changes that caused vibration and noise in older diesel engine designs.

Advanced lean-burn light-duty diesel combustion incorporates a number of specific advanced engine technologies including: Direct Fuel Injection, Electronic Fuel Injection, High Pressure Fuel Injection (including Common Rail systems and Hydraulic Electronic Unit Injection systems), Improved Combustion Chamber Design, and Advanced Turbo Charging. Each of these advancements are discussed in more detail in the attached Clean Diesel Technology Appendix.

2. Advanced Light-duty Diesel Emissions Control Technologies

New technologies directed specifically at controlling certain emissions have dramatically improved emissions performance.

While diesels naturally perform better than gasoline engines with respect to CO, HC and CO_2 emissions, diesel combustion tends to produce more PM and NOx than is produced by gasoline engines. NOx emissions from gasoline engines have been effectively limited by the use of catalyst technology, whereas the sulfur in diesel fuel has historically prevented use of similar, conventional catalysts in the diesel sector. Diesel engines also produce more PM than gasoline engines. Increased PM emissions result from incomplete combustion caused by the low level of oxygen around individual fuel droplets in the combustion zone. The lean-burn engines, though they produce less PM than traditional diesels, still tend to emit higher levels of PM than conventional gasoline-fueled engines. In Europe, the NOx/PM emissions challenge has been met with a variety of new technologies that have made light-duty diesel engines much cleaner, and future progress is anticipated.

For example, last year Peugeot introduced the first modern, mass produced automobile equipped with a diesel particulate filter. Particulate filters were first introduced to German diesels sold in California in the 1980s, but it was soon discovered that these traps would clog quickly with soot and they have not been used on diesel cars since. The latest Peugeot particulate filter has solved the earlier technical problems by developing a filter system that can “regenerate” or cleanse itself of excess soot as the vehicle operates. The Peugeot filter system has enabled Peugeot’s high pressure direct injection engine to achieve a diesel particulate emissions reduction of more than 95%. The Peugeot system uses the engine’s advanced common rail fuel injection system to increase the temperature of exhaust when necessary to oxidize or burn excess soot from the filter. The filter is automatically regenerated every 250-300 miles. Complete regeneration takes only two to three minutes, and has no effect on driving.[20]

The availability of low sulfur diesel fuel in Europe has enabled substantial emissions reductions to be achieved, both through advanced exhaust treatment technologies like Peugeot's particulate traps, which capture engine emissions before they leave the tailpipe, and through catalytic converters that convert emissions to harmless substances. The European Union has enacted diesel fuel sulfur limits applicable to all Member States. The diesel sulfur limit, which was reduced to 350 ppm in 2000 and will be further lowered to 50 ppm in 2005, has enabled use of the more aggressively formulated catalysts, and generally improved the longevity and effectiveness of many of these emissions control systems. "Sulfur-free" diesel, which has a sulfur content of 10 ppm or less, has been available in Sweden for more than a decade. More recently, it has been introduced in the U.K. Both countries support sulfur-free fuels with tax incentive programs. Germany has enacted tax incentives for 50 ppm fuel effective November, 2001, and incentives for 10 ppm starting in 2003. Recently the European Commission has adopted a proposal to introduce sulfur-free diesel in every Member State by 2011.

In addition to advanced aftertreatment technologies and low-sulfur diesel fuel, other engine enhancements like air-to-air charge cooling and exhaust gas recirculation have also contributed to significant improvements in NOx emissions. These emission control technologies are discussed in more detail in the attached Clean Diesel Technology Appendix.

IV. THE EUROPEAN REGULATORY BALANCE – CAPTURING THE BENEFITS OF DIESEL

Environmental regulation typically involves a compromise of objectives. Engine technologies have different emissions profiles, and the choice of emissions standards can amount to a prescription of technology. The upcoming U.S. light-duty emissions standards (Tier 2) accommodate gasoline engines, which emit relatively little NOx but much more CO, HC and CO_2. By emphasizing control of NOx and PM instead of greenhouse gases, the new U.S. standards hinder the use of diesel engines. Europe has struck a different balance. With PM, where emissions reduction technology is developing the fastest, regulatory emissions reductions have been the most aggressive. At the same time, standards for NOx have ratcheted down more slowly to reflect the technological limitations in achieving those types of reductions. This balanced approach to NOx and PM restrictions has been combined with market-based incentives for increasing fuel economy that allow Europe to capture the improved fuel efficiency and lower CO, HC and CO_2 emissions of advanced light-duty diesel technology.

A. Market-Based Incentives: Encouraging the Use of Diesel to Reduce Greenhouse Gas Emissions and Limit Oil Imports

Although there are still many uncertainties regarding the issue of global climate change, greenhouse gas emissions are seen as a critical public policy issue in Europe. The European Union has committed itself to reducing greenhouse gas emissions by some 8% below 1990 levels between 2008 and 2012, and most European governments have already begun to implement policies designed to meet those goals. [21]

In the automotive sector, the greenhouse gas of greatest concern is carbon dioxide. Diesel engines emit far less CO_2 than gasoline-powered engines, and Europeans have embraced diesel technology as one of the preferred methods of cutting carbon emissions from mobile sources. Diesel's greenhouse gas advantage is directly related to its excellent fuel efficiency. Carbon dioxide is a primary byproduct of the combustion of carbon-based fossil fuel, so reduced fuel consumption reduces CO_2 emissions.[22]

European governments encourage the use of diesel technology through market-based programs that reward the purchase of fuel efficient vehicles. In contrast to the U.S. command-and-control approach of setting Corporate Average Fuel Economy standards that mandate fuel efficiency levels from the supply-side, European governments have adopted fuel and vehicle tax structures that influence the buying behavior of consumers. For instance, many European countries have significant fuel taxes that drive the price of gasoline up to more than $4/gallon. [23] These taxes, which represent about 75% of the price at the pump, cause Europeans to favor more fuel efficient vehicles such as diesel passenger cars. [24] A majority of European countries have even gone beyond fuel-neutral policies, and employ tax policies that cause diesel fuel to be 8-28% cheaper than gasoline. [25]

Some European countries have also established diesel vehicle sales tax incentives. For instance, Austria has adopted a vehicle sales tax based inversely on fuel economy, therefore taxing fuel-efficient diesel vehicles at a much lower rate.[26]

European governments favor such tax policies not only as a means to cut greenhouse gas emissions, but also as an effective method of reducing reliance on oil imports. In the United States, the Department of Energy has estimated that increasing the market share of light-duty diesel technology to 30% by 2010 (still below the level already achieved in Europe) would reduce net crude oil imports by 700,000 barrels per day by 2020—an amount equivalent to cutting in half the total energy used each day in the state of California.[27]

The European tax policies applied to fuels and vehicles are strongly supported by the European environmental community. Many European environmental groups have made global climate change a top priority. These groups support the high fuel taxes that magnify the importance of fuel efficiency in selecting an automobile.[28] In contrast to their American counterparts, these groups have been far more accepting of new diesel technologies, and have concentrated on advocating for the use of ultra-low sulfur diesel fuel rather than attacking diesels in general.[29]

B. Emissions Standards

Emission regulations are the other key element that distinguishes American and European diesel policies. The new U.S. light-duty emission regulations set upcoming standards that will make it extremely difficult to market advanced diesel technology. The European Union has taken a more pragmatic approach, designing diesel engine emission regulations to encourage the development of cleaner diesel engines and the use of ultra low sulfur diesel fuel while maintaining the technology's market viability.

1. European Union Standards

The European Union has adopted uniform diesel engine emission regulations (see Table 1). Like the U.S. regulations, these standards become progressively more stringent over time. The baseline was established by the EURO I standards in 1992. Automanufacturers are already meeting the stringent EURO III standards that went into effect in 2000, and are developing the technology that will allow them to comply with EURO IV in 2005.

Table 1: E.U. Emission Standards for Diesel Passenger Cars[30]

	Particulates (g/km)	NOx (g/km)	NOx + HC (g/km)	CO (g/km)
EURO I (1992)	0.14	--	0.97	2.72
EURO II (1996) Direct Injection	0.1		0.9	1
Indirect Injection	0.08	--	0.7	1
EURO III (2000)	0.05	0.5	0.56	0.64
EURO IV (2005)	0.025	0.25	0.3	0.5

2. United States Standards

The regulatory structure in the United States is more complicated. In simple terms, the United States federal government sets the primary emissions limits for mobile sources. The State of California is allowed to maintain a separate regulatory scheme that is more stringent than the federal standards, and any state may choose to follow the California standards instead of the federal rules. While there are significant differences between the current federal and California programs, the U.S. EPA has recently decided to amend the federal standards in a way that will limit those differences.

The new federal regulations—called Tier 2 standards—will begin to take effect in 2004. After a phase-in period, Tier 2 will be fully-implemented in 2009. The final Tier 2 structure establishes eight certification "bins" in which manufacturers must certify their fleets (see Table 2). Although manufacturers can choose which vehicles will be certified in which bin, the end result for each manufacturer must be a fleet-wide average NOx limit of 0.07 g/mi. Unlike the current standards, the Tier 2 regulations do not provide separate NOx standards for diesel-powered vehicles, and they will cover even the heaviest SUVs and passenger vans.

Table 2: U.S. Tier 2 Fully Implemented (2009) Standards (g/mi); All Passenger Vehicles (< 10,000 lbs & < 13 passengers); Full Useful Life (120,000 miles)

Certification Bin	NOx	Non-methane Organic Gases	CO	Formaldehyde (HCHO)	PM
8	0.20	0.125	4.2	0.018	0.02
7	0.15	0.090	4.2	0.018	0.02
6	0.10	0.090	4.2	0.018	0.01
5	0.07	0.090	4.2	0.018	0.01
4	0.04	0.070	2.1	0.011	0.01
3	0.03	0.055	2.1	0.011	0.01
2	0.02	0.010	2.1	0.004	0.01
1	0.00	0.000	0.0	0.000	0.00

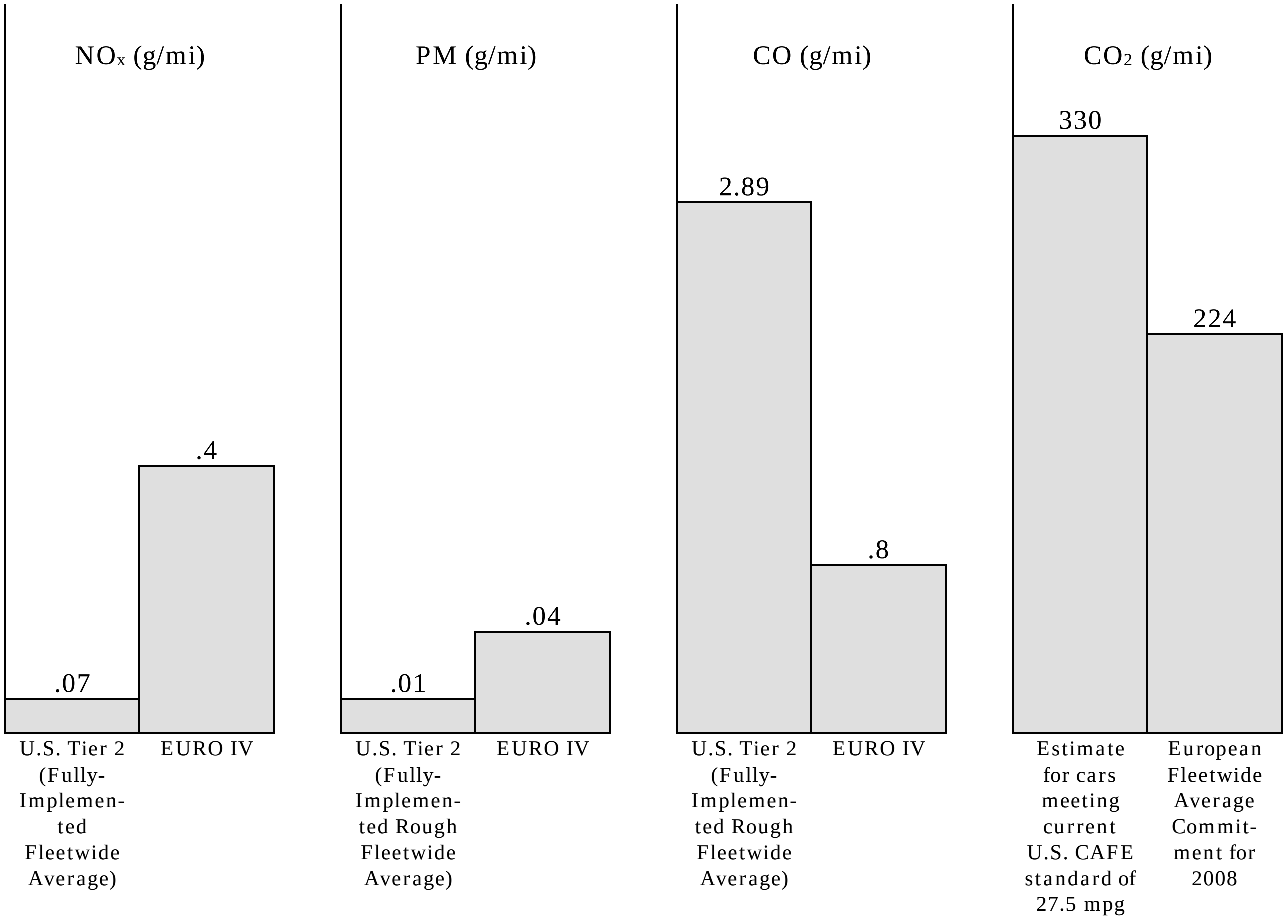
3. Comparing the Standards

Comparing European standards to U.S. standards is a complicated task. In each system, emissions are measured during specific test cycles, designed to simulate typical vehicle operation. U.S. and E.U. test cycles are different, however,

so the emission standards are not directly comparable. The two systems also use different regulatory approaches. The E.U. standards set emission caps applied to each vehicle, while the new U.S. standards set a fleet-wide average NOx limit. The two systems also regulate slightly different sets of pollutants.

Notwithstanding these differences, it is still possible to draw the general conclusion that the upcoming U.S. standards for light-duty diesel vehicles are more stringent than the EURO IV standards in some respects, but less strict in others.[31] See Figure 2. For instance, the Tier 2 standards are more strict with respect to NOx and PM standards than the EURO IV regulations. At the same time, the U.S. standards allow more CO emissions than the European standards. Moreover, the United States has not made the same type of substantial CO_2 emission reductions recently agreed to in Europe, where car manufacturers and the European Union have agreed to reduce fleet-wide average CO_2 emissions to 140 g/km (about 224 g/mile) by 2008.[32] This figure compares to the estimated average of 330 g/mile of CO_2 emissions emitted by passenger cars in the United States. In making the voluntary commitment to reduce average CO_2 emissions, European auto-makers are relying on their high market-penetration of diesel vehicles—a market penetration that would not exist if European car manufacturers were also required to comply with the U.S. Tier 2 NOx and PM standards.

Figure 2: Comparing U.S. and E.U. Emission Regulations



V. THE POTENTIAL OF LIGHT-DUTY DIESEL IN THE UNITED STATES

U.S. policy-makers have only recently turned their attention back to fuel economy as a means to reduce American dependence on imported crude oil, lower the impact of high gasoline prices, and limit the amount of greenhouse gases emitted by the transportation sector. The European light-duty diesel experience establishes a well developed track record on the advantages of light-duty diesel power that should be carefully examined by American policy makers in the current energy crisis. An examination of the American light-duty vehicle market reveals that the U.S. is particularly well suited to take advantage of the diesel power solutions that already play an important role in Europe.

1. U.S. Diesel Solutions For Today

Diesel is a proven and readily available technology. Given appropriate and balanced regulatory requirements and cleaner fuels, the fuel efficiency advantages of diesel can be achieved immediately without requiring consumers to bear the expense and delay of additional investments in research and development. The diesel has been tested and refined for more than a century and its versatility and reliability are legendary.

Diesel power is also cost-effective. The few models of diesels available to American consumers today demonstrate that light-duty diesel vehicles cost individual consumers less than the money it saves them through reduced fuel costs. For example, a 2001 turbo-diesel Jetta GLS costs $500 dollars less than the turbocharged gasoline powered Jetta GLS [33] and the owner of a diesel Jetta can expect to save over $2300 in fuel costs over a 100,000 mile vehicle life at year 2000 fuel prices.[34]

Fuel cost savings with diesel are proportionally greater for larger vehicles handling heavier loads. The owner of a 1999 diesel Ford F-250 Super-duty pickup truck would pay $1,650 more for a diesel powered version, but because the diesel gets 46% better mileage under towing conditions, the diesel owner would save over $8,000 in fuel costs over the course of 100,000 miles.[35] The proportional effect of these fuel savings is particularly significant in the context of the U.S. auto market where nearly half of all new vehicles sold are SUVs, vans or pickups.[36]

Because diesel engines are more powerful than gasoline engines, producing more drive force at lower engine speeds, they are perfectly suited for improving the fuel economy of today's vast U.S. light truck/SUV market. Nearly all of the growth in U.S. vehicle sales over the past 25 years has been in light trucks. Light trucks, which include SUVs, pick-ups and vans, have seen annual sales grow from 2 million to nearly 7.5 million since 1975. Today, light trucks account for nearly one of every two vehicles sold in the U.S.[37] The average new SUV/light truck currently gets 20.7 mpg compared to 28.1 for the average new car. Application of diesel technology in the SUV market could immediately increase the nation's average fuel economy by targeting a large market share of vehicles that currently achieve lower fuel economy ratings due to their size.

The power and efficiency of diesels can also be used to reduce nationwide fuel consumption without the safety compromises associated with building lighter vehicles. Numerous studies by the National Highway Traffic Safety Administration, the National Academy of Sciences, the Harvard Center for Risk Assessment, and the Insurance Institute for Highway Safety have found that vehicle weight reductions in the early 1980's tended to reduce vehicle safety and led to thousands of additional vehicle fatalities.[38] Because diesel engines are more powerful and more fuel efficient at the same time, the use of diesel allows fuel economy improvements to be realized without building lighter, less safe vehicles.

Because of the size of vehicles driven in the United States and the popularity of automobile transportation, the United States has the potential to reap substantially greater fuel and emissions savings than the less automobile-oriented European countries. In 1992, automobile miles-per-capita in the U.S. were nearly four times the per-capita automobile miles traveled in France, Italy, the former West Germany and Great Britain combined.[39] The number of vehicle miles traveled in the U.S. has doubled since 1970 and is expected to rise by an additional 50% by 2020. The average fuel economy for all passenger vehicles on the road in the U.S. is 20.6 mpg. Thus, American drivers on average use many more gallons of gas than their European counterparts. Because Americans burn more fuel, the potential for fuel savings and corresponding CO_2 emissions savings from increased use of diesel is much greater than the savings experienced in Europe. As noted above, the U.S. Department of Energy has estimated that increasing the market share of light-duty diesel technology to 30% would reduce net crude oil imports by 700,000 barrels per day by 2020 – an amount equivalent to cutting in half the total energy used each day in the state of California.[40]

2. Diesel Solutions for Tomorrow

The most efficient European direct-drive (non-hybrid) diesels already surpass the fuel efficiency of the most advanced gasoline/electric hybrids sold in the U.S. Combining the superior efficiency of diesel engines with the efficiencies of hybrid electric vehicles can provide even greater fuel efficiencies.

The logic of using the most efficient internal combustion engines in hybrid electric vehicles has already been recognized by all of the major U.S. automakers working in the Partnership for a New Generation of Vehicles (PNGV). The PNGV is a joint government-industry partnership organized to cooperate in the development of the next generation of radically more fuel efficient and environmentally friendly vehicles. The goal of the PNGV program is to develop an affordable class of five-passenger mid-size vehicles that get 80 mpg while maintaining the performance and cost of ownership of existing vehicles. The PNGV engineering teams have now worked toward this goal for eight years and have invested more than $2 billion, exploring technologies such as fuel cells and electric hybrids. The most promise to date has been shown by diesel electric hybrid technology. Last year, each of the three major U.S. auto-makers introduced prototypes of the new so-called "super-cars" and each featured diesel electric hybrid engines along with advanced aerodynamics and a number of new weight saving vehicle technologies. The

General Motors Precept, Dodge ESX3, and Ford Prodigy prototypes all achieve better than 70 mpg using diesel electric power.[41] Although the prototype PNGV vehicles using diesel technology are already coming very close to the 80 mpg target, developing such vehicles that also meet the low Tier 2 NOx standard remains a significant challenge with a very uncertain outcome.

VI. CONCLUSION—HARNESSING DIESEL INNOVATION FOR FUEL ECONOMY AND EMISSIONS OBJECTIVES

Even in this age of globalization, the light-duty diesel markets in the United States and Europe remain a world apart. European policymakers have recognized the environmental advantages of diesel, and have allowed new diesel vehicles to prove themselves as efficient, quiet, and powerful alternatives. In America, growth in the market share of light-duty diesels would vastly reduce fuel consumption, foreign oil imports, and greenhouse gas emissions. Moreover, new technology has greatly reduced diesel's NOx and PM emissions, and advanced developments will continue to reduce these emissions. Despite these advantages, and despite the regulatory path taken in Europe, American policymakers have created a regulatory structure that greatly impedes the widespread use of diesel vehicles. Consequently, Americans may be denied the performance, fuel economy and environmental benefits of advanced diesel technology.

[1] http://www.wardsauto.com

[2] Ward's Automotive Yearbook, 63rd ed., p.59 (2001)

[3] Walsh, M.P., "Global Trends in Diesel Emissions Regulation: A 2001 Update," SAE 2001-01-0183 (March 2001); Love, M., "Diesel Passenger Car and Light Commercial Vehicle Markets in Western Europe," Ricardo Consulting Engineers Ltd (March 2001)

[4] http://www.dieselnet.com/news/9811peugeot.html

[5] "Communication from the Commission to the Council and the European Parliament: Implementing the Community Strategy to Reduce CO_2 Emissions from Cars. First annual report on the effectiveness of the strategy," Commission of the European Communities (April 10, 2000)

[6] "Communication from the Commission to the Council and the European Parliament: Implementing the Community Strategy to Reduce CO_2 Emissions from Cars. First annual report on the effectiveness of the strategy," Commission of the European Communities (April 10, 2000); Love, M., "Diesel Passenger Car and Light Commercial Vehicle Markets in Western Europe," Ricardo Consulting Engineers Ltd (March 2001)

[7] Love, M., "Diesel Passenger Car and Light Commercial Vehicle Markets in Western Europe," Ricardo Consulting Engineers Ltd (March 2001); Reigber, B., "European Auto Makers Are Banking on Popularity of Diesel Engines," The Wall Street Journal Europe (April 26, 2001); "France Expects Car Ahead to be Peugeot," Birmingham Post (June 26, 2001)

[8] "Auto 2000: Annual Report of the German Automotive Industry (VDA)," available at http://www.vda.de/en/service/jahresbericht/auto2000/auto+umwelt/u_6.html

[9] "Sales of Diesels Will Reach Limits of Fuel Supply," Hart's European Fuels News (Aug. 2, 2000)

[10] "New leading diesel technology from Volvo Car Corporation – VOLVO D5 – POWER AND PLEASURE," available at http://vcc.volvocars.se/index.asp

[11] "New leading diesel technology from Volvo Car Corporation – VOLVO D5 – POWER AND PLEASURE," available at http://vcc.volvocars.se/index.asp

[12] "Engineering Clean Air: The Continuous Improvement of Diesel Engine Emission Performance," Diesel Technology Forum (March, 2001)

[13] "Engineering Clean Air: The Continuous Improvement of Diesel Engine Emission Performance," Diesel Technology Forum (March, 2001)

[14] According to the 2001 EPA Fuel Economy Guide, the combined city/highway fuel economy for the five-speed manual transmission, 1.9 liter diesel Jetta TDI is 45 mpg (42 City/49 Highway), while the same car with a 2.0 liter gasoline engine gets 27 mpg (24 City/31 Highway).

[15] http://www.wardsauto.com

[16] http://www.fueleconomy.gov

17 http://www.vw.com/jetta/engspec.htm

18 "Legacy of Leadership: Isuzu's Diesel Engine Program," Isuzu Motors Ltd.

19 http://www.psa.fr/techno/diesel/anglais/esp_chiffres.html

20 http://www.peugeotavenue.com/innov/

21 "Economic Evaluation of Sectoral Emission Reduction Objectives for Climate Change: Top-down Analysis of Greenhouse Gas Emission Reduction Possibilities in the EU," (2001) available at http://europa.eu.int/comm/environment/enveco/climate_change/top_down_analysis.pdf

22 http://www.vcacarfueldata.org.uk/e_introduction.htm#CARSANDFUELOPTIONS; http://www.sae.org/news/dieseff.htm

23 Graham, J.D., "Civilizing the Sport Utility Vehicle," Issues in Science & Technology (Jan. 1, 2000)

24 Morris, J., "Poetic Justice: The Real Culprits of High Fuel Taxes," The Wall Street Journal Europe (Sept. 19, 2000)

25 Love, M., "Diesel Passenger Car and Light Commercial Vehicle Markets in Western Europe," Ricardo Consulting Engineers Ltd (March 2001). In some cases, European nations are maintaining a much lower tax rate only for ultra-low sulfur diesel fuel. CLID p.67; Taschner, 2000; Prasad, 1998.

26 Diesel Information and Liaison Committee at http://www.diesel-info.com/Reception.html

27 "The Impacts of Increased Diesel Penetration in the Transportation Sector," Office of Integrated Analysis and Forecasting, Energy Information Administration, U.S. Department of Energy (Aug. 1998); "Diesel Technology and the American Economy," Charles River Assoc. (Oct. 2000)

28 Morris, J., "Poetic Justice: The Real Culprits of High Fuel Taxes," The Wall Street Journal Europe (Sept. 19, 2000)

29 Andrews, E.L. & Bradsher, K., "It Gets 78 Miles a Gallon, but U.S. Snubs Diesel," The New York Times (May 29, 2001); "Cash: Friend of the Earth: How to Step Off the Gas," The Observer (Nov. 19, 2000); Watson, C., "Green Campaigners Praise Bus Firm's Switch to Cleaner Fuel in City," The Herald (United Kingdom) (Oct. 12, 1998)

30 Diesel Information and Liaison Committee at http://www.diesel-info.com/Reception.html

31 Bradsher, K., "Diesel Engines Get Spotlight in Fuel-Efficiency Contest," The New York Times (June 12, 2001); Andrews, E.L. & Bradsher, K., "It Gets 78 Miles a Gallon, but U.S. Snubs Diesel," The New York Times (May 29, 2001)

32 "Communication from the Commission to the Council and the European Parliament: Implementing the Community Strategy to Reduce CO_2 Emissions from Cars. First annual report on the effectiveness of the strategy." Commission of the European Communities (April 10, 2000)

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[33] Based on Manufacturer's Suggested Retail Prices available at http://www.vw.com/jetta/engspec.htm

[34] Based on U.S. Dept. of Energy's weekly Petroleum Status Reports average U.S. retail fuel prices for August, 2000 (Diesel $1.46/Gasoline $1.50) and MY 2001 U.S. EPA Fuel Economy Ratings.

[35] "Diesel Technology and the American Economy," Charles River Assoc. (Oct. 2000)

[36] "Drilling in Detroit: Tapping Automaker Ingenuity to Build Safe and Efficient Automobiles," Union of Concerned Scientists & Center for Auto Safety (June 2001)

[37] "Drilling in Detroit: Tapping Automaker Ingenuity to Build Safe and Efficient Automobiles," Union of Concerned Scientists & Center for Auto Safety (June 2001)

[38] http://www.vehiclechoice.org/safety/size.html

[39] Schipper, L. "Determinants of Automobile Use and Energy Consumption in OECD Countries," Annu. Rev. Energy Environ. (1995)

[40] "The Impacts of Increased Diesel Penetration in the Transportation Sector," Office of Integrated Analysis and Forecasting, Energy Information Administration, U.S. Department of Energy (Aug. 1998); "Diesel Technology and the American Economy," Charles River Assoc. (Oct. 2000)

[41] http://www.ta.doc.gov/pngv/

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Clean Diesel Technology Appendix

1. Advanced Lean-burn Combustion Technologies

- ***Direct Fuel Injection:*** Direct fuel injection is an essential component of lean-burn diesel combustion. Direct injection technology has long been used in heavy-duty diesel engines world-wide. Until recently, most light-duty, automobiles sized diesel engines have used indirect injection technology. Direct injection engines inject fuel and air directly into the cylinder, while an indirect injection engine uses a prechamber to help mix the fuel and air before it enters the main cylinder. Indirect injection comes with a substantial fuel efficiency penalty compared to direct injection because the prechamber permits additional energy losses. Until recently, the additional fuel air mixing provided by the prechamber was essential for diesel passenger vehicles. The small, high-speed engines used in cars generally require fuel and air to mix 10 times faster than in larger engines, something that until recently has been difficult to achieve without a prechamber. The latest direct injection technologies, discussed in more detail below, have been able to improve the fuel air mixing, making light-duty diesels more fuel efficient and reducing emissions.
- ***Electronic Fuel Injection.*** The development of electronic fuel injection controls has also played a central role in improving light-duty diesel performance. Electronic systems calibrate fuel injection based on information from electronic sensors that monitor engine performance and vehicle activity. They are used both to ensure a more complete fuel burn to reduce PM, and to control temperature to reduce NOx. In contrast, older diesel fuel injection systems used mechanical means to control the quantity and timing of fuel injection. With those systems, rapid ramp-up of engine speed – such as acceleration with a heavy load – led to excess fuel being injected. Much of this fuel was not burned and was emitted as soot (PM), which created the black exhaust that many Americans associate with older diesel engines.

- ***High pressure fuel injection.*** Fuel efficiency and PM emissions are improved through more complete combustion of fuel injected into the combustion chamber. More complete combustion can be achieved by improving the mix of air and fuel in the chamber. Modern high-pressure direct fuel injection systems force fuel into the combustion chamber through smaller diameter holes at higher pressure – in excess of 25,000 pounds per square inch. This causes the fuel to break down into tiny droplets, thereby improving the air-fuel mix to achieve a more complete burn.

Today's light-duty European diesels use the very latest generation of advanced electronic high pressure direct fuel injection systems to improve emissions and overall engine performance. In these systems, injection pressure and injection rate can be controlled independently of engine speed and load, which is a departure from traditional fuel systems. Specific advanced fuel injection technologies include Common Rail Systems and Hydraulic Unit Injection systems.

In a Common Rail System (CRS), fuel is held in a reservoir, or "rail," that serves all of the engine's cylinders: a "common" rail. Fuel in the common rail is maintained under pressure, and that pressure does not vary with engine speed. Instead, pressure can be controlled independently to achieve emissions objectives.

Hydraulic Electronic Unit Injection (HEUI) systems also provide for lower emissions while improving fuel economy and performance. In these systems, individual unit injectors are actuated hydraulically by a high pressure oil pump, rather than mechanically. This high pressure oil controls the rate of injection, while electronics control the amount of fuel injected. All of this is done independently of engine speed.

These advanced systems enable a number of emissions-reducing fuel injection techniques that previously were infeasible. For example, to reduce NOx emissions, fuel injection can be geared independently to control burn temperature. In order to reduce particulate emissions, the main fuel injection can be split into two, causing a more complete burn of fuel. Likewise, combustion noise can also be reduced by causing one or more small injections of fuel in advance of the main injection to reduce the sudden temperature and pressure changes that cause vibration and noise in older diesel engine designs.

- ***Turbocharging.*** Turbocharging both reduces PM emissions and improves fuel economy. A turbocharger compresses the air that enters the cylinder, forcing more air into the combustion chamber. The compressor is driven by a turbine, which in turn is powered by the engine's own exhaust. The increase in air in the combustion chamber offers two key advantages. First, it enables fuel to burn more completely, reducing PM. Second, it permits more fuel to be added to the chamber, generating more power than a similarly-sized engine without turbocharging. By generating more power from a smaller displacement engine, turbocharging improves engine efficiency, reduces engine weight and improves fuel economy. European diesel passenger cars commonly use the very latest generation of variable geometry turbine (VGT) turbochargers. In fact, today roughly half of all new European light-duty diesels in the 1.2 - 1.4 liter range feature VGT turbochargers.

VGT turbochargers work by adjusting the size of the air passage at the turbine wheel inlet in order to optimize turbine power. At low engine speeds, when the exhaust gas flow at the turbine wheel inlet is low, the air passage at the inlet is focused by a nozzle. This causes the turbine wheel to spin faster and increases the turbocharger's boost pressure. In contrast, at high engine speeds and loads, which create greatly increased exhaust flow, the inlet nozzle opens to moderate turbine speed and turbocharger boost pressure. Variable geometry turbochargers thus have a quicker response time during vehicle acceleration, and at the same time prevent over-boosting at high speeds. This allows the vehicle to nearly eliminate the black puff of smoke during acceleration and to burn fuel more efficiently over the full range of operation, producing less emissions and achieving better fuel economy.

- ***Improved combustion chamber configuration.*** More complete fuel combustion, and reduced PM emissions occur when fuel and air are mixed more evenly in the combustion chamber. European manufacturers have worked to optimize the features of combustion chambers to ensure the best possible mix. Modern combustion chamber design reflects extensive refinements of several design elements, including: (1) the shape and depth of the combustion chamber and the piston bowl (the small area at the top of the piston into which fuel is injected); (2) spiral-shaped intake ports that cause air to swirl as it enters the chamber; (3) the number of cylinder valves; and (4) the placement of fuel injectors in the combustion chamber.

2. Advanced Diesel Emissions Control Technologies:

- ***Oxidation Catalysts.*** Flow-through oxidation catalysts significantly reduce emissions of carbon monoxide, hydrocarbons and PM. Oxidation catalysts initiate a chemical reaction in the exhaust stream, oxidizing pollutants into water vapor and other gases, such as sulfur dioxide and carbon dioxide. A typical oxidation catalyst consists of a stainless steel canister containing a honeycomb-like structure called a substrate. The interior surfaces of the substrate are coated with catalytic precious metals, such as platinum or palladium. Oxidation catalysts are sensitive to the sulfur in diesel fuel, which tends to reduce the effectiveness of the catalyst. Lower fuel sulfur content allows catalysts to be formulated aggressively in Europe to achieve substantial emissions reductions.

- ***Particulate Filters.*** The latest generation of European light-duty diesels also use advanced particulate filter systems. These systems consist of a filter positioned in the exhaust stream to collect particulate emissions as the exhaust gases pass through the system.

The latest Peugeot particulate filter system achieves a reduction of more than 95% in diesel particle emissions. The particulate filter itself is a porous structure made of silicon carbide, which traps the particles as the exhaust fumes pass through it.

To maintain maximum performance, the filter has to be regularly regenerated or cleansed by periodically burning the accumulated particles. In the presence of oxygen, this combustion occurs naturally when the temperature of the exhaust exceeds 550°C. This temperature is far above those observed in the HDI engine's usual operating range. In order to burn the particles, two techniques are used. First, the "common rail" injection system is used to increase the temperature of the exhaust in two stages: 1) a post-injection of fuel in the expansion phase creates afterburning in the cylinder and leads to an increase in temperature of between 200° and 250°C; 2) a complementary afterburning operation, generated by an oxidizing catalyst placed upstream from the filter, processes those hydrocarbons left unburned following the post-injection. This increases the temperature by an additional 100°C or more. A second process is used to lower the natural combustion temperature of the collected particles. Eolys, an albanite-based compound manufactured by Rhodia is added to the fuel to lower the natural particle combustion temperature to 450°C. Regeneration occurs automatically about every 400 to 500 km depending on the degree of clogging of the filter. Complete regeneration takes only two or three minutes, and occurs in a way that has no effect on driving.

- ***NOx Catalysts.*** Two catalyst technologies are being developed specifically to reduce NOx emissions. The first, so-called “lean NOx catalyst” works like selective catalytic reduction in that it adds a reducing agent to the exhaust stream to facilitate catalytic conversion. Systems using lean NOx catalysts inject diesel fuel into the exhaust gas to add hydrocarbons. The hydrocarbons act as a reducing agent to facilitate the conversion of NOx to nitrogen and water vapor in the catalyst.

  The second technology, “NOx Adsorbers” operates in two stages. First, the NOx is converted and adsorbed into a chemical storage site within the system. Then when the NOx adsorber becomes saturated, it is regenerated by adding extra diesel fuel to the exhaust stream. The addition of the fuel causes the NOx adsorber to work like a lean NOx catalyst -- it converts the collected NOx into simple nitrogen and oxygen which is emitted from the system.

- ***Air-to-air charge cooling.*** This is a further advance in turbocharging that is used in European passenger cars to reduce NOx emissions. Turbochargers deliver (or "charge") air at higher pressure, and therefore also increase the temperature of the air delivered for combustion. Air-to-air charge cooling reduces the temperature of the charged air, thereby lowering NOx emissions. Ambient air, which averages about 75° F, is used to cool the air to be charged in the combustion chamber. This is an improvement on the water-based cooling systems that had been used in the past. Those systems were limited in their effectiveness by their use of water at temperatures that could run as high as 210° F.
- ***Exhaust Gas Recirculation.*** Exhaust gas recirculation ("EGR") provides significant NOx reductions. EGR reduces NOx by reducing the temperature at which fuel burns in the combustion chamber. Engines employing EGR recycle a portion of engine exhaust back to the engine air intake. The oxygen-depleted exhaust gas is mixed into the fresh air that enters the combustion chamber, which dilutes the oxygen content of the air in the combustion chamber. The reduction in oxygen produces a lower temperature burn, and hence reduces NOx emissions. The recycled exhaust gas can also be cooled, which further reduces NOx emissions.

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