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Light-Duty Diesel Vehicles: Market Issues and Potential Energy and Emissions Impacts

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Preface and Contacts

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EIA's Office of Integrated Analysis and Forecasting (OIAF) prepared this report. General questions concerning industry statistics described in the report can be directed to John J. Conti (john.conti@eia.doe.gov, 202/586-2222), Director of the Office of Integrated Analysis and Forecasting; Paul Holtberg (paul.holtberg@eia.doe.gov, 202/586-1284), Director of its Demand and Integration Division; and Michael Schaal (michael.schaal@eia.doe.gov, 202/586-5590) Director of its Oil and Gas Division. Specific questions about the report can be directed to the following analysts:

Greenhouse Gas Analysis .... John Maples (john.maples@eia.doe.gov, 202/586-1757)
Nicholas Chase (nicholas.chase@eia.doe.gov, 202/586-8851)
Vehicle Market Analysis............... John Maples (john.maples@eia.doe.gov, 202/586-1757)
Nicholas Chase (nicholas.chase@eia.doe.gov, 202/586-8851)
Diesel Market Analysis................. Peter Gross (peter.gross@eia.doe.gov, 202/586-8822)

For ordering information and questions on other energy statistics available from EIA, please contact EIA's National Energy Information Center at:

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Contents

Tables

Figures

Executive Summary

This report responds to a request from Senator Jeff Sessions for an analysis of the environmental and energy efficiency attributes of light-duty diesel vehicles.[1] Specifically, the inquiry asked for a comparison of the characteristics of diesel-fueled vehicles with those of similar gasoline-fueled, E85-fueled,[2] and hybrid vehicles, as well as a discussion of any technical, economic, regulatory, or other obstacles to increasing the use of diesel-fueled vehicles in the United States.

Energy Efficiency

Diesel-fueled vehicles generally are more fuel-efficient than comparable gasoline-fueled vehicles. In fuel economy (miles per gallon) ratings published by the U.S. Environmental Protection Agency (EPA), diesel vehicles show a fuel economy advantage of 20 to 40 percent over gasoline vehicles, depending on the size and duty requirements of the vehicles. The EPA fuel economy ratings also suggest that diesel vehicles are somewhat less fuel-efficient than the most comparable gasoline-powered hybrid-electric vehicles; however, comparisons are difficult, because differences in performance characteristics, such as torque, may force consumers to balance fuel economy against other desired performance attributes. Additionally, on-road driving experience appears to suggest that, under some circumstances, diesel vehicles can achieve higher fuel efficiencies than comparable gasoline-powered hybrids.

For flex-fuel vehicles (FFVs)—which use slightly modified versions of the engines in gasoline vehicles and are capable of burning mixtures of gasoline and ethanol up to E85—fuel economies are lower when they use E85 fuel than when they use gasoline. The difference largely reflects the lower energy content of ethanol than of gasoline. For flex-fuel engines that incorporate advanced technologies, however, E85 fuel efficiency can be improved by as much as 18 percent.

In comparison with conventional gasoline vehicles, diesel vehicles are inherently more efficient for two reasons:

- Diesel engines operate at higher compression ratios than do spark-ignited gasoline engines, creating higher in-cylinder temperatures, more complete combustion, and higher thermal efficiency.
- The energy content of diesel fuel per gallon is 11 percent greater than the energy content of gasoline.

Greenhouse Gas Emissions

On a "well-to-wheels" basis, which incorporates emissions associated with direct activities from the start of the fuel cycle to fuel combustion, greenhouse gas (GHG) emissions from diesel vehicles using diesel fuel are estimated to be 15 percent lower than emissions from comparable vehicles using gasoline but still 20 to 25 percent higher than emissions from gasoline- or diesel-powered hybrid electric vehicles (HEVs). GHG emissions from gasoline- or diesel-powered plug-in hybrid electric vehicles (PHEVs), which use power from the electricity grid for a portion of their propulsion, are 16 to 32 percent lower than emissions from diesel vehicles using diesel fuel.

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[1]The request letter from Senator Sessions is provided in Appendix A.
[2]E85 is a blended fuel containing 15 percent gasoline and 85 percent ethanol.

For vehicles that use E85, B20,[3] and other biofuels, comparisons of GHG emissions are less clear for three reasons:

- First, total GHG emissions vary according to the feedstock and production process used to make the biofuels. For example, ethanol produced from cellulosic materials is expected to have significantly lower life-cycle GHG emissions than corn-based ethanol.

- Second, comparisons are sensitive to the treatment of the “indirect emissions” that result from adjustments in land use (such as the clearing of forest from land in developing countries that is used to cultivate energy crops for increased production of biofuels in response to rising prices). Indirect emissions are a complex and contentious issue, and they were not included in the model that was used to provide the well-to-wheels calculations for this study.

- Third, diesel vehicles can use a variety of biofuels. In addition to B20, a fuel that is available now, EIA projects that high-quality biomass-to-liquids (BTL) diesel fuels, using technologies that have been demonstrated successfully in gas-to-liquids (GTL) and coal-to-liquids (CTL) applications, ultimately will meet a portion of the mandate for cellulosic biofuels included in the Energy Independence and Security Act of 2007 (EISA2007). The use of BTL in efficient diesel engines would result in very low GHG emissions.

With those important caveats in mind, however, some comparisons can be made.

- For diesel vehicles using B20, GHG emissions are 18 percent lower than for diesel vehicles using diesel fuel and 30 percent lower than for vehicles using gasoline (see Chapter 2, Table 2.1).

- Excluding consideration of indirect emissions, direct emissions of GHGs from diesel vehicles using diesel fuel are 4 to 137 percent higher than for FFVs using E85, depending on whether the ethanol is produced from corn or cellulosic material.

- Direct emissions of GHGs from diesel vehicles using B20 are 95 percent higher than for FFVs using cellulosic ethanol but 14 percent lower than for FFVs using corn-based ethanol.

- For HEVs that use conventional engines, E85 in flex-fuel engines, or B20 in diesel engines, GHG emissions are 20 to 71 percent lower than for diesel vehicles using diesel fuel and 4 to 65 percent lower than for diesel vehicles using B20.

- For PHEVs, GHG emissions are 16 to 63 percent lower than for diesel vehicles using diesel fuel but may be higher than for diesel vehicles using B20, depending on the energy source used to generate the electricity, the engine type, and the type of fuel used by the vehicle.

U.S. and European Markets for Light-Duty Diesel Vehicles

Light-duty diesel vehicles have been offered in the U.S. market for several decades. In 2007, they accounted for 1.7 percent of all U.S. sales of new light-duty vehicles. The vast majority of U.S. diesel sales are light trucks, although some manufacturers based in Europe offer diesel-powered cars in U.S. markets. In the early 1980s, U.S. automakers developed and marketed several diesel-powered car models. U.S. sales of light-duty diesel vehicles peaked at 5.5 percent of light-duty vehicle sales in 1981, but the cars were plagued by poor performance, fuel quality problems, declining fuel prices, and severe reliability problems. As a result, consumers rapidly lost interest, and in 1988 new diesel car sales had declined rapidly to only a 0.2-percent share of new car sales.

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[3]B20 is a blended fuel containing 20 percent biodiesel and 80 percent diesel fuel.

Since 1988, diesel vehicles have accounted for less than 1 percent of all new car sales.[4] In contrast, the diesel engines offered in light trucks have proven to be very reliable, and they continue to be favored in a niche market.

Diesel-fueled vehicles have had much greater success in Western European markets. Over the past decade, sales of diesel vehicles in Western Europe have climbed from 28.4 percent of total light-duty vehicle sales to 52.2 percent. Belgium, France, and Spain have aggressively promoted light-duty diesel vehicles, and as a result sales shares in those countries currently exceed 70 percent.

In Western Europe, policy decisions on the taxation of fuels and vehicles, along with emissions standards, have had a significant role in increasing the use of diesel vehicles. Policy decisions have been instrumental in raising fuel economy to reduce oil consumption, and although the initial impetus appears to have been energy security, fuel economy increasingly is viewed in the context of reducing GHG emissions. Three main policy factors have contributed to the market success of diesel vehicles in Western Europe:

- Higher retail fuel prices, mostly as a result of taxes, cause consumers to seek out vehicles with high fuel economy ratings, favoring diesel over gasoline engines because of their substantial fuel economy advantage over gasoline vehicles of similar power.

- In many countries, taxation policies favor diesel vehicles, with lower vehicle taxes and registration fees for diesel vehicles than for comparable gasoline vehicles.[5]

- European standards for emissions of nitrogen oxides (NO_x) accommodate the use of diesel vehicles to a much greater extent than do U.S. standards.

In the United States, in contrast, there are several impediments to the market success of diesel vehicles. They include more stringent Federal and State standards for vehicle emissions, cost premiums for diesel vehicles, limited availability of light-duty diesel vehicles, and higher retail prices for diesel fuel than for conventional gasoline.

U.S. standards for tailpipe emissions of NO_x, which have been tightened over time, pose a particular challenge for diesel vehicles. Effective with the 2009 model year, Federal Tier 2 vehicle emission standards require that the vehicle fleet produced by each manufacturer meet an average NO_x emissions level of 0.07 grams per mile. California standards, which also are applicable in 10 other States, require the same NO_x emissions limit to be met by each individual vehicle. For marketing reasons, U.S. manufacturers are selling only light-duty diesel vehicles that comply with the California standard and thus can be sold in all 50 States.

The effective NO_x standard of 0.07 grams per mile required for light-duty diesel vehicles to be compliant in all 50 U.S. States is significantly more stringent than the standard applicable to light-duty diesel vehicles in Western Europe. The Euro 5 NO_x vehicle emission standard, which will take effect in September 2009, is 0.18 grams per kilometer (0.29 grams per mile). The current Euro 4 NO_x vehicle emission standard is equivalent to 0.4 grams per mile.

Compliance with the tighter U.S. requirements, where feasible, generally involves additional emissions control equipment and higher costs. Thus, depending on the manufacturer, the

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[4]S.C. Davis, S.W. Diegel, and R.G. Boundy, *Transportation Energy Data Book: Edition 27*, ORNL-6981 (Oak Ridge, TN, 2008), Table 4.5, web site http://cta.ornl.gov/data/index.shtml.
[5]U. Kunert and H. Kuhfeld, "The Diverse Structures of Passenger Car Taxation in Europe and the EU Commissions Proposal for Reform," Discussion Paper 589 (Berlin, Germany: Deutsches Institut für Wirtschaftsforschung, May 2006), web site http://ideas.repec.org/p/diw/diwwpp/dp589.html.

incremental cost of diesel vehicles over gasoline vehicles in the U.S. market ranges from $1,000 to $7,195. In addition, the emissions control systems often use chemicals that require careful handling and periodic refilling, both of which can reduce the attractiveness of diesel vehicles to consumers.

The wide range of incremental costs for diesel vehicles over gasoline vehicles in the U.S. market reflects the pricing strategies of automobile manufacturers and the costs of other included equipment. The cost of vehicles that can meet U.S. and California emissions standards may be offset somewhat, however, by the recent extension (in the Emergency Economic Stabilization Act of 2008) of eligibility for the Alternative Motor Vehicle Credit to qualifying diesel vehicles,[6] allowing tax credits of $900 to $1,800 for model year 2009 vehicles. The full credit is provided for the first 60,000 vehicles sold by a manufacturer, after which the amount is reduced by 50 percent for the following two calendar quarters and to 25 percent of the original credit for the next two calendar quarters, after which no credit is allowed.

For consumers interested in purchasing a new light-duty diesel vehicle, there are very few vehicles available for consideration. In addition, Honda, Chrysler, Hyundai, and Toyota have canceled or delayed their planned offerings of diesel products, citing high incremental costs for diesel fuel, the costs of emission control equipment, and limited consumer interest as reasons for their decisions.[7]

Exclusive of general trends in crude oil prices, the price of diesel fuel in the United States has increased by more than the price of gasoline in recent years. As a result, the operating cost advantage of diesel vehicles over gasoline vehicles has been reduced or, in extreme cases, eliminated. From 1994 to 2004, on an annual average basis, the retail price of gasoline was 5 cents per gallon (4 percent) higher than the price of diesel fuel.[8] During that period, diesel was typically more expensive than gasoline during the winter months but cheaper during the summer months. From 2005 to 2007, however, the price pattern was reversed, with diesel being 7 cents per gallon (3 percent) more expensive than gasoline. The difference grew larger in 2008, when the diesel price was, on average, 50 cents per gallon (15 percent) higher than the price of gasoline.

The increasing price premium for diesel relative to gasoline is attributable to a variety of factors, including the transition to ultra-low-sulfur diesel (ULSD) that began in mid-2006, the availability of extra gasoline supplies from Western European countries as a result of their transition to diesel, reductions in U.S. demand for petroleum-based gasoline components that resulted from increased use of ethanol in gasoline, and the growing importance of developing countries, whose demand is heavily oriented toward diesel, in world oil markets.

Although the U.S. price premium for diesel relative to gasoline is expected to shrink from its 2008 level, the continued growth of demand for diesel fuel in developing countries, along with environmental policies that favor increased use of diesel as a substitute for fuel oil—including efforts to reduce the sulfur content of marine bunker fuels used in domestic and international commerce—suggest that diesel fuel may continue to be priced at a premium relative to gasoline in the United States.

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[6]26 U.S. Code 30B, "Alternative Motor Vehicle Credit." See web site www.irs.gov/businesses/article/0,,id=175456,00.html.
[7]See web site http://wardsauto.com (subscription site): **Chrysler:** E. Mayne, "Bluetec Grand Cherokee Rollout on Rocks" (September 10, 2008); **Toyota:** E. Mayne, "Diesel-Powered Tundra Under Review" (October 1, 2008); **Honda:** C. Schweinsberg, "Honda Cancels Acura Diesel" (October 30, 2008); **Hyundai:** C. Schweinsberg, "Hyundai To Introduce Stop-Start in U.S.; Drops S-Diesel Plan" (January 13, 2009).
[8]Energy Information Administration, "Petroleum Navigator: Weekly Retail Gasoline and Diesel Prices," web site http://tonto.eia.doe.gov/dnav/pet/pet_pri_gnd_dcus_nus_a.htm.

Taken together, increased vehicle costs and higher prices for diesel fuel currently provide an economic disincentive for purchases of diesel vehicles by U.S. consumers. For those who do purchase diesel vehicles, other vehicle attributes, including durability, longevity, and power output, are likely to be important considerations. Finally, in addition to the issues raised above, there are other consumer preference factors at work in the U.S. vehicle market. For example, unsatisfactory consumer experience with domestic diesel cars during the early 1980s may have reduced the number of people who would consider purchasing a diesel-powered car today (although the impact of the 1980s experience on consumer acceptance is likely to attenuate over time).

A U.S. policy that could incentivize sales of diesel vehicles is EISA2007, which significantly raised fuel economy standards. In order to meet those standards while also meeting consumers' expectations for vehicle performance, manufacturers are likely to incorporate a wide range of advanced drive trains in their new vehicles over the coming years. Diesel is one of those technologies. In EIA's *Annual Energy Outlook 2009* reference case,[9] the diesel share of total light-duty vehicle sales is projected to grow from 1.7 percent in 2007 to 10 percent in 2030. In addition, a variety of other advanced technology vehicles are projected to increase in market share. As a result, the total market share for all hybrid vehicles is projected to increase from 2.3 percent in 2007 to 39 percent in 2030.

[9]Energy Information Administration, *Annual Energy Outlook 2009* reference case, AEO2009 National Energy Modeling System run AEO2009.D120908A.

1. Introduction

This report responds to a request from Senator Jeff Sessions for an analysis of light-duty diesel vehicles, including an examination of relevant technical, economic, regulatory, and environmental issues that could have impacts on market acceptance.[10] The report provides an analysis and assessment of the issues and reports the findings in three chapters that address the topical areas of interest.

GHG reductions could be achieved through increased sales of conventional diesel vehicles as compared to conventional gasoline vehicles; however, competing technologies and alternative fuels could provide equivalent or greater reductions. Currently, as options to reduce petroleum demand and GHG emissions, hybrid and flex-fuel vehicles compete with diesel vehicles as alternatives to conventional gasoline vehicles. Projections of direct well-to-wheels GHG emissions and associated GHG reductions for different vehicle types are presented and discussed in Chapter 2.

Diesel engines are inherently more fuel-efficient than gasoline engines due to attributes associated with the combustion process and the properties of diesel fuel. Diesel vehicles produced and sold today are technically superior to those produced 20 years ago, but lingering consumer perceptions associated with the older diesels have kept sales at a minimum. This, coupled with the cost of emission control equipment required to meet new tailpipe emission standards, has created marketing issues for manufacturers and limited product offerings. In contrast, Western European countries have enacted tax polices that support light-duty diesel vehicles and have proven successful. These issues are examined in detail in Chapter 3.

Prices for highway diesel fuel in the United States currently reflect a cost premium due to imbalances between supply and demand in global markets. The refining industry's ability to adjust output to keep pace with demand, as well as the continued growth in global demand, will determine how long these price premiums will persist. Issues related to world refining capacity, petroleum fuel demand, and refining technologies are discussed in Chapter 4.

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[10]The request letter from Senator Sessions is provided in Appendix A.

2. Comparison of Light-Duty Vehicle Greenhouse Gas Emissions

This section provides a comparison of diesel vehicle GHG emissions and GHG emissions from conventional gasoline vehicles, HEVs, FFVs, and PHEVs, using the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) well-to-wheels model. According to the GREET model, GHG emissions from diesel vehicles are lower than from conventional gasoline vehicles, an advantage that is amplified by the use of biodiesel. However, HEVs, FFVs, and PHEVs, all potential competitors with diesel vehicles as alternative vehicle technologies, provide equivalent or increased reductions in direct GHG emissions compared to diesel vehicles.

The transportation sector is the second-largest emitter of GHGs by end use in the United States, accounting for 28 percent of all GHGs emissions in 2007.[11] GHG emissions are unregulated in the United States but continue to garner significant attention both domestically and internationally because of concerns about climate change. Diesel-powered vehicles have entered the climate change debate because proponents claim that they have lower GHG emissions than conventional gasoline vehicles.[12] This report uses the GREET model, developed by the Argonne National Laboratory, to examine and compare projections of GHG emissions from diesel vehicles with those from other vehicle types, including FFVs, HEVs, and PHEVs, in 2010.[13]

According to the GREET model, total well-to-wheel GHG emissions from diesel vehicles using diesel fuel are 15 percent lower than those from comparable gasoline vehicles using E10 (Table 2.1). For diesel vehicles using B20, GHG emissions are 18 percent lower than those from diesel vehicles using diesel fuel, widening a diesel vehicle's emission reduction over gasoline counterparts to 30 percent. Diesel vehicles using diesel fuel emit between 4 and 137 percent more direct GHGs than FFVs using E85, depending on whether the ethanol is produced from corn or cellulosic material. Diesel vehicles using B20 emit 95 percent more direct GHGs than FFVs using cellulosic ethanol but 14 percent less than FFVs using corn-based ethanol. HEVs emit between 20 and 71 percent less GHGs than diesel vehicles using diesel fuel and between 4 and 65 percent less than diesel vehicles using B20, depending on the HEV engine or fuel type. PHEVs, which use power from the electricity grid for a portion of their propulsion, emit between 16 and 63 percent less GHGs than diesel vehicles using diesel fuel but may emit more GHGs than diesel vehicles using B20, depending on the energy source used to generate the electricity.

GREET's GHG emissions model provides an accounting of GHGs emitted through the entire fuel cycle and reports comparable well-to-wheels emissions rates for a variety of light-duty vehicle fuel and technology combinations. In the well-to-wheels calculation, emission rates are estimated for three stages of the fuel cycle: feedstock, fuel production, and vehicle operations. The feedstock stage includes those emissions created from the collection of an energy-bearing resource, such as the production of crude oil from an oil field or the growing of corn for ethanol, as well as transportation to the refinery gate. The fuel stage includes those GHGs emitted during the process of turning a feedstock into the fuel that can be used by a vehicle, such as processing crude oil into gasoline or diesel fuel or turning soybean oil or grease into biodiesel, as well as transporting these fuels to retail facilities. Together, the feedstock and fuel stages comprise the "well-to-pump" portion of the well-

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[11]Energy Information Administration, *Emissions of Greenhouse Gases in the United States 2007*, DOE/EIA-0573(2007) (Washington, DC, December 2008), web site www.eia.doe.gov/oiaf/1605/ggrpt/index.html.
[12]J.A. DeVore and E.R. Fanick, "Impact of Ultra-Clean Fischer-Tropsch Diesel Fuel on Emissions in a Light-Duty Passenger Car Diesel Engine," SAE International Document No. 2002-01-2725 (October 2002), web site www.sae.org/technical/papers/2002-01-2725 (subscription site).
[13]Results taken from Argonne National Laboratory's Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model, Version 1.8b.

to-wheels fuel cycle. Finally, the GHG emissions from the actual operation of the vehicle, also referred to as the "pump-to-wheels" cycle, are estimated.

Table 2.1. Total (Well-to-Wheels Cycle) Direct Greenhouse Gas Emissions for Various Vehicle Types, 2010 (Grams per Mile)

Fuel Type	Vehicle Type				
	Conventional	Hybrid Electric	Plug-in Hybrid Electric		
			U.S. Grid	Northeast U.S. Grid	California Grid
Gasoline					
E10	476	322	340	312	289
E85 (FFV)					
Corn	389	263	302	274	250
Cellulosic	171	116	203	175	151
Diesel					
Diesel Fuel	405	305	328	301	277
B20	334	230	279	251	227

Source: Results taken from the Argonne National Laboratory's Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model, Version 1.8b.

It is important to note that the GREET model projects GHG emissions from direct land-use changes but does not project emissions from indirect land-use changes.[14] Direct land-use changes involve direct displacement of land for farming of the feedstocks needed for biofuel production; indirect land-use changes are those made to accommodate farming of food commodities in other places in order to maintain the global balance of food supply and demand.[15] Measuring indirect emissions is a complex and often contentious, though potentially important, issue.[16] Because indirect emissions resulting from land-use change are not included in GREET, they are not included in this report. A complete table of GREET's well-to-wheels direct GHG emissions projections for 2010 is provided in Appendix B.

Based on projections of GHG emissions associated with the well-to-pump portion of the full fuel cycle, diesel vehicles using diesel fuel emit 18 percent less GHGs than conventional gasoline vehicles using E10 (Table 2.2). At the feedstock stage, there is essentially no difference between GHG emission rates for gasoline and diesel fuel, because both follow similar production paths; however, at a refinery the process for making diesel fuel is less energy-intensive than the process for making gasoline on a Btu basis. Consequently, making diesel fuel from petroleum emits less GHGs in the fuel stage than making gasoline. Blending 10 percent ethanol made from corn into gasoline slightly reduces the GHG emissions compared to conventional gasoline in the well-to-pump cycle,

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[14]For a discussion of greenhouse gas emissions and indirect land use changes, see T. Searchinger, R. Heimlich, R.A. Houghton, et al., "Use of U.S. Croplands for Biofuels Increases Greenhouse Gases Through Emissions from Land-Use Change, *Science*, Vol. 319, No. 5867 (February 29, 2008), pp. 1238-1240, web site www.sciencemag.org/cgi/content/abstract/1151861 (subscription site).
[15]M. Wang and Z. Haq, "Letter to *Science*" (March 14, 2008), web site www.transportation.anl.gov/pdfs/letter_to_science_anldoe_03_14_08.pdf.
[16]U.S. Department of Energy, Office of Policy Analysis, *World Biofuels Production Potential: Understanding the Challenges to Meeting the U.S. Renewable Fuel Standard* (Washington, DC, September 2008), web site www.pi.energy.gov/documents/20080915_WorldBiofuelsProductionPotential.pdf.

because corn at the feedstock level is a GHG sink, meaning that it removes carbon dioxide from the atmosphere during photosynthesis. However, at the fuel stage, making corn ethanol is a highly energy-intensive process, offsetting much of the GHG reductions at the feedstock stage.

Table 2.2. Well-to-Pump Cycle Direct Greenhouse Gas Emissions for Various Vehicle Types, 2010 (Grams per Mile)

	Vehicle Type				
			Plug-in Hybrid Electric		
Fuel Type	Conventional	Hybrid Electric	U.S. Grid	Northeast U.S. Grid	California Grid
Gasoline					
E10	92	62	166	138	115
E85 (FFV)					
Corn	12	7	130	102	78
Cellulosic	-206	-140	31	3	-21
Diesel					
Diesel Fuel	75	57	162	135	111
B20	3	-19	112	84	60

Source: Results taken from the Argonne National Laboratory's Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model, Version 1.8b.

Diesel vehicle GHG emissions associated with the feedstock and fuel stages are reduced by 96 percent when using biodiesel blends, because biodiesel is made from soybeans or other plants that serve as a carbon sink. If diesel fuel is mixed with biodiesel in a blend of 80 percent diesel fuel and 20 percent biodiesel (i.e., B20), GHG emissions in the well-to-pump stage are almost zero. This is because GHG emissions in the feedstock stage of B20 are *negative*, meaning more GHG is removed from the atmosphere than emitted, and emissions at the fuel stage are low due to the relative ease with which biodiesel can be made from soybean oil.

FFVs using E85 achieve direct GHG emission reductions from the well-to-pump cycle relative to diesel vehicles using diesel fuel. Ethanol in the United States currently is made mostly from corn, but there are large-scale scientific and industrial efforts underway to produce cellulosic ethanol from other herbaceous plants.[17] At the feedstock stage, both corn and cellulosic E85 are GHG sinks. At the fuel stage, however, there is a considerable difference in GHG emissions between corn and cellulosic ethanol because of the higher energy input needed to make corn ethanol and the reductions gained from the utilization of cogeneration at cellulosic ethanol plants. A conventional diesel vehicle using B20 emits more GHGs than an FFV using cellulosic E85 but emits less GHGs than an FFV using corn-based E85.

GHG emissions attributed to the well-to-pump cycle for HEVs are less than those from a conventional diesel vehicle using diesel fuel and either higher or lower than those from a conventional diesel vehicle using B20, depending on the HEV engine or fuel type. If the HEV uses cellulosic E85 or B20, then GHG emission reductions exceed those of a diesel vehicle using B20. GREET measures GHG emissions at each stage on a grams per mile basis that is based on the fuel

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[17]U.S. Department of Energy, Energy Efficiency and Renewable Energy, "Biomass FAQs," web site http://www1.eere.energy.gov/biomass/biomass_basics_faqs.html.

economy of that vehicle. Thus, for HEVs, emission reductions in the well-to-pump cycle result from their fuel economy gains in the vehicle operations stage. The fuel economy improvement of HEVs over diesel vehicles is described in more detail below.

Conventional diesel vehicle GHG emissions associated with the well-to-pump cycle are generally lower than those for PHEVs that draw energy from the electricity grid. PHEVs are unique in that they utilize battery power at the start of a trip to drive the vehicle for a distance until a minimum level of battery power is reached. The vehicle then operates on a hybrid mixture of battery and internal combustion traction, the same as an HEV. The PHEV battery is then recharged by plugging the vehicle into an electrical outlet using a power cord, much like recharging a cellular phone.

In the GREET model, PHEVs are assumed to travel 33 percent of vehicle miles traveled in all-electric mode and the remaining 67 percent using the hybrid electric-gasoline engine. Because PHEVs use electricity for a portion of their propulsion, electricity generation is an important factor in their GHG emissions. Electricity generation in the United States uses large amounts of fossil fuels, especially coal, meaning that producing the fuel (electricity) needed by a PHEV emits high levels of GHGs relative to a refinery producing diesel fuel at the fuel stage. Even increasing the share of non-GHG-emitting renewable fuels, such as the electricity grids of the Northeastern United States or California, PHEV fuel-stage emissions are still higher than those for a conventional diesel vehicle if the PHEV uses E10 gasoline.[18]

Conventional diesel vehicles using diesel fuel emit less GHG in the well-to-pump cycle than PHEVs equipped with diesel engines using diesel fuel or B20, or equipped with flex-fuel engines using corn-based E85. Only by using a flex-fuel engine with E85 made from cellulosic material does a PHEV emit less GHG than a diesel vehicle using diesel fuel in the well-to-pump stage. A conventional diesel vehicle using B20 emits 90 percent less GHGs than a PHEV using cellulosic E85 when the vehicle is recharged using the average U.S. electricity grid; it emits the same amount of GHGs when the PHEV is recharged in the U.S. Northeast region, where slightly more non-GHG-emitting renewable fuels are used for electricity generation than the national average; and it emits more GHGs than a PHEV recharged in California, where the percentage of renewable fuels used for electricity generation is much higher than the national average.

In the pump-to-wheels cycle, conventional diesel vehicles using diesel fuel and B20 emit 14 percent less GHGs than conventional gasoline vehicles using E10 (Table 2.3). This is directly related to diesel vehicles' fuel economy advantage over conventional gasoline vehicles. Greater fuel efficiency means that less fuel is used to travel each mile, translating directly into lower GHG emissions because such emissions are a byproduct of the burning of carbon-based fossil fuels.

Diesel vehicles emit 12 percent less GHGs than FFVs in the pump-to-wheel stage. This reduction results from the fuel efficiency advantage of diesel engines over flex-fuel engines. FFVs using E85 have lower fuel economy than diesel vehicles, because the heat content of ethanol is 84,600 Btu per gallon, lower than either diesel fuel or gasoline.[19] This means that relatively more E85 must be burned to achieve the same energy output as diesel fuel. For an FFV using E85, fuel economy is reduced by about 15 percent from a similar gasoline vehicle and by 40 to 65 percent from a similar diesel vehicle.[20] However, if a flex-fuel engine is optimized to take advantage of the fuel properties

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[18]For a breakdown of the different feedstocks used for electricity generation in the GREET model, see Appendix C.
[19]See Appendix C.
[20]P. Valdes-Dapena, "Hybrid vs. Diesel vs. Flex-Fuel," CNNMoney.com, web site http://money.cnn.com/galleries/2007/autos/0706/gallery.alf_fuel_basics/index.html.

of E85, its fuel economy can be increased by up to 18 percent on a Btu equivalent basis, which, depending on relative fuel prices, would make it competitive with diesel vehicles.[21]

Table 2.3. Pump-to-Wheels Cycle Direct Greenhouse Gas Emissions for Various Vehicle Types, 2010 (Grams per Mile)

Fuel Type	Vehicle Type				
	Conventional	Hybrid Electric	Plug-in Hybrid Electric		
			U.S. Grid	Northeast U.S. Grid	California Grid
Gasoline					
E10	384	260	174	174	174
E85					
Corn (FFV)	377	256	172	172	172
Cellulosic (FFV)	377	256	172	172	172
Diesel					
Diesel Fuel	330	248	166	166	166
B20	331	249	167	167	167

Source: Results taken from the Argonne National Laboratory's Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model, Version 1.8b.

HEVs in the pump-to-wheel cycle emit from 21 to 25 percent less GHGs than conventional diesel vehicles using diesel fuel or B20. HEVs achieve relatively high fuel economy because they use an onboard self-recharging battery that shuts off the internal combustion engine at idle and restarts it when needed in acceleration. Because of the battery, HEVs use less carbon-containing fossil fuel, cutting GHG emissions in the process. An HEV equipped with a compression ignition engine using either diesel fuel or B20 can achieve even further GHG reductions by utilizing the fuel efficiency advantages of both the onboard battery and the diesel engine.

PHEVs achieve large GHG emissions reductions—between 47 and 50 percent—compared to diesel vehicles using diesel fuel or B20 in the pump-to-wheels stage. A PHEV using electric power is highly efficient at converting electricity to propel the vehicle, achieving about 105 miles per gallon in electricity mode. Also, when a PHEV switches to its HEV system, it maintains a fuel economy advantage over a diesel vehicle. PHEVs can slightly increase their fuel economy advantage even further by adding a diesel engine.

[21]Fuel economy improvement of E85 optimized engine based on fuel economy data published for the Saab 9-5 2.3t BioPower compared to fuel economy data published for a Saab 2.3T Turbo.

3. Benefits, Past Experience, and Current Market Issues

This chapter provides a brief description of the inherent efficiency benefits associated with diesel engines relative to competing technologies and a historical perspective of the light-duty diesel vehicle market in the United States compared with the relative success realized in European markets. Consumer misconceptions and legacy perceptions of diesel vehicle quality, carried over from the 1980s, have limited their current market acceptance in light-duty vehicle offerings.[22] This, coupled with manufacturers' concerns about the costs associated with the EPA's stringent Tier 2 emissions standards and the difficulty of meeting them, have deterred diesel product offerings in the light-duty vehicle market.[23] In addition, incremental costs for diesel vehicles, consumer preferences, and competition from other advanced technologies could potentially limit the U.S. market penetration of diesel vehicles.

Efficiency Benefits

Diesel engines offer significant fuel economy gains over conventional spark-ignited engines. Depending on vehicle size and duty requirements, vehicles with diesel engines typically achieve 20 percent to 40 percent better fuel economy than their conventional gasoline counterparts of comparable size and performance.[24]

Diesel vehicles are inherently more efficient for two reasons:

- First, diesel engines operate at higher compression ratios than gasoline-powered engines, creating higher in-cylinder temperatures and more complete combustion and providing higher thermal efficiency. Diesel engines take air into the engine cylinders, compress it to very high compression ratios (up to 20:1) that cause the air to reach a high temperature, and then directly inject diesel fuel into the highly compressed high-temperature air, spontaneously igniting the fuel. This process differs from a gasoline engine, where a mixture of gasoline and air is drawn into the engine cylinder through an intake, compressed at a lower compression ratio and lower temperature than diesel, and ignited with a spark. Because the higher in-cylinder temperature of diesel engines burns fuel more easily, and because highly compressed air allows more of the closely packed fuel molecules to combust, diesel engines can burn less fuel than gasoline engines to complete the combustion event.
- Second, diesel fuel has a higher volumetric energy content than gasoline. The heat content for diesel is 138,700 Btu per gallon, compared with 125,000 Btu per gallon for gasoline, meaning that diesel fuel has a higher energy density than gasoline per gallon.[25] A higher energy density means that less diesel fuel needs to be combusted relative to gasoline to achieve the same energy output. Together, a diesel engine's greater thermal efficiency and the higher energy density of the fuel provide a decided fuel economy advantage over conventional spark-ignited gasoline engines.

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[22]B. Pope, "BMW Expects Slow Acceptance of New Diesel Offerings in U.S.," WardsAuto.com (January 14, 2008), web site http://wardsauto.com/reports/2008/naias/bmw_diesel_acceptance/.
[23]E. Mayne, "Bluetec Grand Cherokee Rollout on Rocks," WardAuto.com (September 10, 2008), web site http://subscribers.wardsauto.com/ar/blutec_grand_cherokee_080910 (subscription site).
[24]The fuel economy gain of using a diesel engine versus a gasoline engine is taken from www.fueleconomy.gov. A limited number of diesel engine vehicles are sold in the United States. The fuel economy of several diesel vehicles sold in 2008 and 2009 was compared with that of a similar vehicle based on model and vehicle performance.
[25]S.C. Davis, S.W. Diegel, and R.G. Boundy, *Transportation Energy Data Book: Edition 27*, ORNL-6981 (Oak Ridge, TN, 2008), web site http://cta.ornl.gov/data/index.shtml.

Diesel engines are also more fuel-efficient than spark-ignited FFV engines. Flex-fuel engines are unique because they can run on gasoline, alcohol-based fuel (typically, E85), or any mixture of gasoline and alcohol-based fuel. When an FFV is operated using only gasoline, the diesel vehicle outperforms it in terms of fuel economy by the same 20 to 40 percent and for the same reasons that a diesel engine is more fuel-efficient than a gasoline engine. If a vehicle with a flex-fuel engine uses E85, fuel economy will actually decrease, because the heat content of ethanol is only 84,600 Btu per gallon, lower than the heat content of either diesel fuel or gasoline.[26] For an FFV using E85, fuel economy is reduced by about 15 percent from a similar gasoline-powered vehicle and by 40 to 65 percent from a diesel vehicle.[27] If a flex-fuel engine incorporates technologies such as forced-air induction and variable compression ratio, it can take advantage of the fuel properties of E85, and its fuel efficiency can be increased by up to 18 percent on a Btu equivalent basis. Depending on relative fuel prices, the increase in fuel economy could make the FFV competitive with diesel vehicles.[28]

EPA fuel economy tests indicate that diesel vehicles have lower adjusted fuel economy than similar HEVs but generally achieve higher performance ratings for characteristics such as torque. In the compact car size class, Volkswagen's 2009 Turbocharged Diesel Jetta achieves an EPA-adjusted 34 miles per gallon, as compared with a listed fuel economy of 46 miles per gallon for a 2009 Toyota Prius. In the mid-size class, a Mercedes Benz E320 Bluetech diesel achieves 26 miles per gallon, compared with 34 miles per gallon for a similarly sized Nissan Altima Hybrid.

The penalty for the higher fuel economy in hybrid vehicles is often decreased vehicle performance. Torque, directly related to a vehicle's acceleration and towing capacity, is rated at 400 foot-pounds in the Mercedes E320, compared with 320 foot-pounds for the Altima. When the Prius and Jetta are compared, the hybrid does not suffer any performance penalty, because both have similar torque.[29]

When choosing a diesel or HEV, consumers may be forced to balance improved fuel economy against their desired performance needs. Additionally, on-road driving experience seems to indicate that, under some circumstances, diesel vehicles can outperform hybrids in actual fuel economy achieved. For example, in a recent 600-mile European road test from London to Geneva, a diesel-powered mid-sized BMW 520d actually outperformed the fuel economy of a gasoline-hybrid Toyota Prius, with the BMW diesel averaging 41.9 miles per gallon and the hybrid Prius, despite being 500 pounds lighter, averaging only 40.1 miles per gallon.[30] Thus, diesel vehicles may actually exceed the fuel economy of hybrids in real-world driving situations.

U.S. and European Light-Duty Diesel Experience

Light-duty diesel vehicles have been offered in the U.S. market for several decades. In the late 1970s and early 1980s, several manufactures offered diesel engines as optional equipment in their cars and light trucks to meet consumer demand for fuel economy improvement and to help them comply with corporate average fuel economy (CAFE) standards. After several new diesel vehicles were introduced in the late 1970s, diesel vehicle sales increased rapidly, and sales peaked in 1981 at 5.5 percent of new light-duty vehicle sales, coinciding with the peak in the share of car sales at 6.1

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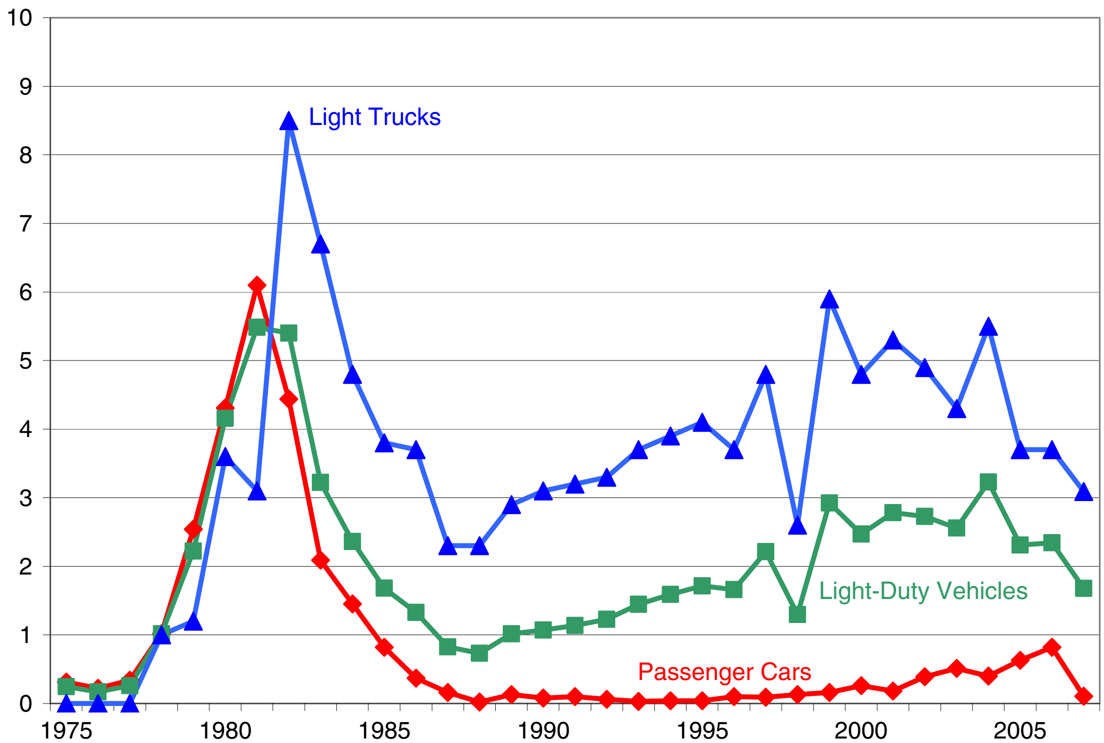
[26]Source: S.C. Davis, S.W. Diegel, and R.G. Boundy, *Transportation Energy Data Book: Edition 27*, ORNL-6981 (Oak Ridge, TN, 2008), web site http://cta.ornl.gov/data/index.shtml.
[27]P. Valdes-Dapena, "Hybrid vs. Diesel vs. Flex-Fuel," CNNMoney.com, web site http://money.cnn.com/galleries/2007/autos/0706/gallery.alf_fuel_basics/index.html.
[28]Fuel economy improvement of E85-optimized engine based on fuel economy data published for the Saab 9-5 2.3t BioPower compared to fuel economy data published for a Saab 2.3T Turbo.
[29]Information taken from www.edmunds.com.
[30]N. Rufford and J. Dawe, "Toyota Prius Proves a Gas Guzzler in a Race with the BMW 520d," *Sunday Times* (March 16, 2008), web site www.timesonline.co.uk/tol/driving/used_car_reviews/article3552994.ece.

percent (Figure 3.1). The following year, the light truck diesel sales share peaked at 8.5 percent. By 1985 General Motors, Ford, Mercedes Benz, Volkswagen, Audi, Nissan, Volvo, Peugeot, and BMW were offering diesel engines in their product lines.

Figure 3.1. Market Shares of U.S. Light-Duty Diesel Vehicles, 1975-2007 (Percent of Total New Vehicle Sales)



Source: S.C. Davis, S.W. Diegel, and R.G. Boundy, *Transportation Energy Data Book: Edition 27*, ORNL-6981 (Oak Ridge, TN, 2008), web site http://cta.ornl.gov/data/index.shtml.

Due to poor vehicle performance, fuel quality problems, declining fuel prices, and severe reliability problems associated with the Oldsmobile diesels, however, consumers quickly lost interest in diesel cars, and by 1988 new diesel car sales had declined to only 0.2 percent of new car sales, and only Mercedes Benz and Volkswagen continued to offer diesel vehicles. Diesel car sales never recovered and have accounted for less than 1 percent of new car sales since 1988.[31] Although new diesel light truck sales also declined rapidly between 1982 and 1988, the diesel engines offered in light trucks were reliable. They continue to be favored by a niche market and have accounted for, on average, about 4 percent of new light truck sales per year over the past 20 years.[32]

In contrast to the United States, diesel engines are widely used in light-duty vehicles in Western Europe. Over the past decade, diesel sales in Western Europe have climbed from 28.4 percent of total light-duty vehicle sales to 52.2 percent (Figure 3.2). Belgium, France, and Spain have enacted policies that aggressively promote light-duty diesel vehicles. As a result, sales shares in those countries currently exceed 70 percent, whereas in the United States the diesel share of new light-duty vehicle sales has declined from 2.9 percent to just 1.8 percent, with a vast majority of the sales being light-duty trucks rather than passenger vehicles. Appendix D provides the percent share of

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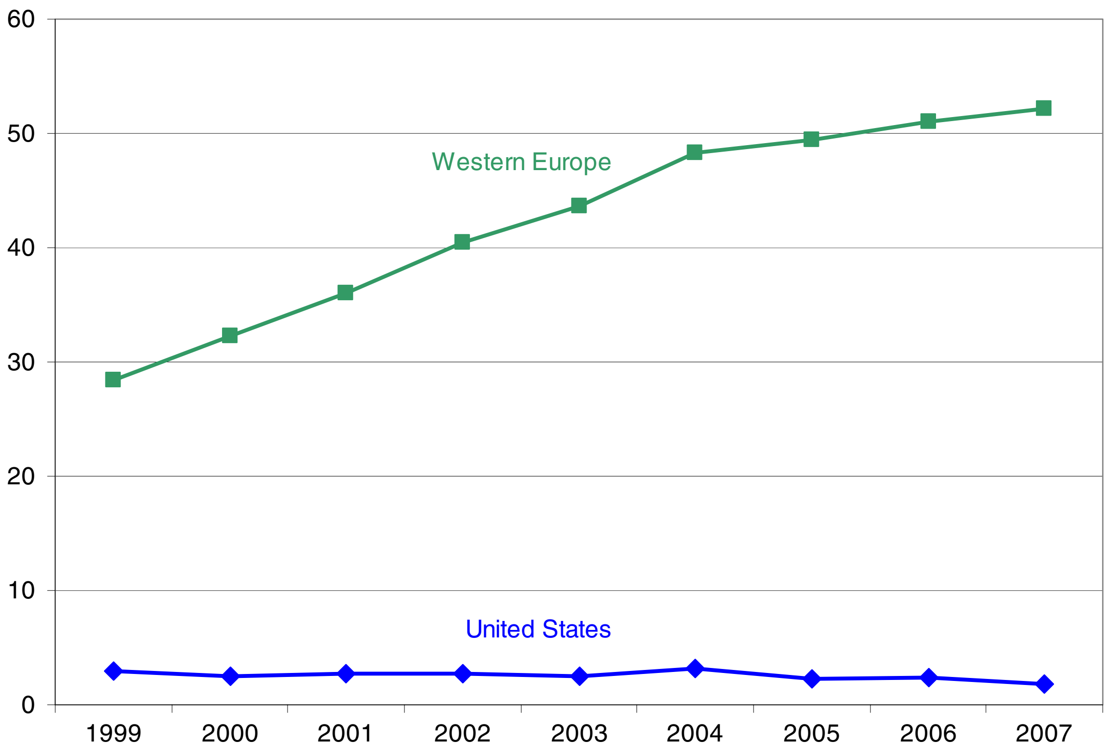
[31]S.C. Davis, S.W. Diegel, and R.G. Boundy, *Transportation Energy Data Book: Edition 27*, ORNL-6981 (Oak Ridge, TN, 2008), Table 4.5, web site http://cta.ornl.gov/data/index.shtml.
[32]S.C. Davis, S.W. Diegel, and R.G. Boundy, *Transportation Energy Data Book: Edition 27*, ORNL-6981 (Oak Ridge, TN, 2008), Table 4.6, web site http://cta.ornl.gov/data/index.shtml.

diesel vehicle sales for various Western European countries and the United States from 1999 to 2007.

Figure 3.2. Diesel Engine Vehicle Market Shares in Western Europe and the United States, 1999-2007 (Percent of Total New Light-Duty Vehicle Sales)



Sources: S.C. Davis, S.W. Diegel, and R.G. Boundy, *Transportation Energy Data Book: Edition 27*, ORNL-6981 (Oak Ridge, TN, 2008), Tables 4-5 and 4-6, web site http://cta.ornl.gov/data/index.shtml; and AID Ltd, *AID Newsletter*, Nos. 0102, 0302, 0501, 0602, 0702, and 0714 (2001-2007), web site www.eagleaid.com/index.htm (subscription site).

There are three principal reasons for the success of diesel vehicles during the past 20 years in the Western European light-duty vehicle fleet compared to the United States: higher retail fuel prices on average, favorable tax policies, and less stringent emissions standards. First, prices across all grades of gasoline and diesel transportation fuels are higher in Europe than in the United States (Figure 3.3). Higher retail prices for both gasoline and diesel cause European consumers to seek out vehicles with high fuel economy ratings, often favoring diesel over gasoline engines because diesels offer substantial fuel economy advantages (20 to 40 percent) over their gasoline counterparts of similar power.[33] The most common type of gasoline used at the pump in Western Europe is 95 RON, equivalent to 91 octane premium-grade gasoline in the United States.

The price comparisons in Figure 3.3 contrast European 95 RON fuel with premium gasoline in the United States to ensure price comparison between similar fuels. It should be noted, however, that 87 octane regular unleaded gasoline in the United States is cheaper and more commonly used than the premium grade, making it even more difficult for diesel vehicles to compete for consumer

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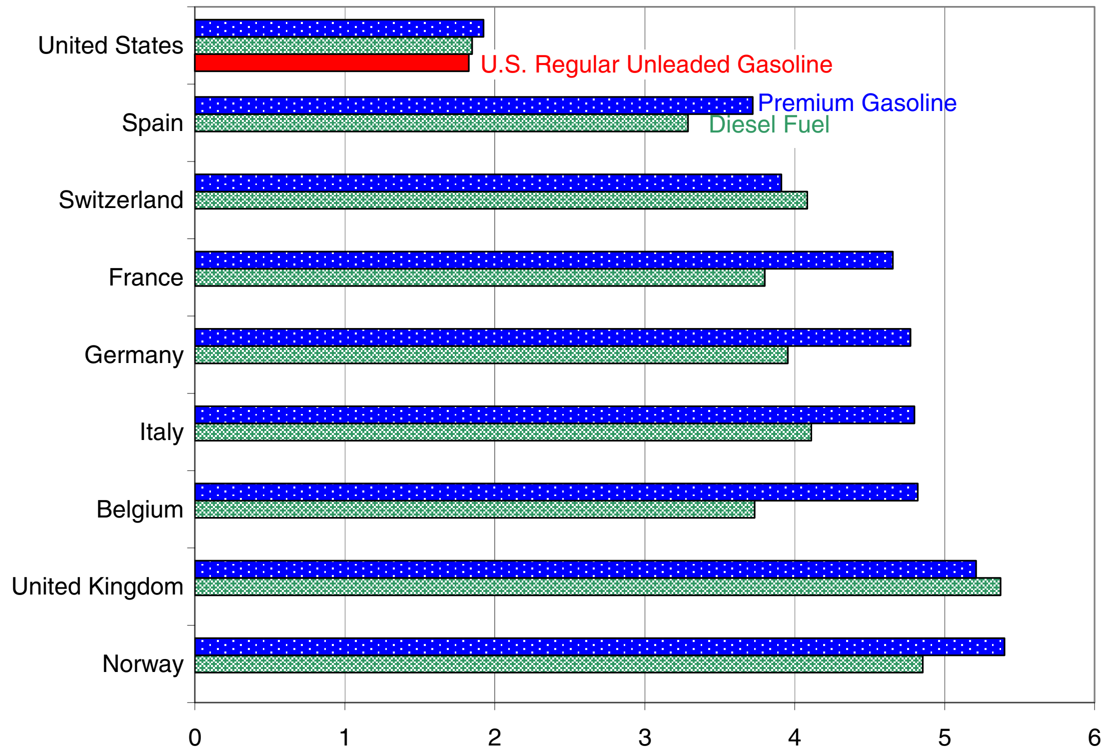
[33]Diesel Technology Forum, *Demand for Diesels: The European Experience* (Frederick, MD, July 2001), web site www.dieselforum.org/news-center/pdfs/EuropeanExperience.pdf/at_download/file; and L. Ulrich, "Diesel Automobiles Clean Up for an Encore," *New York Times* (May 18, 2008), web site www.nytimes.com/2008/05/18/automobiles/18DIESEL.html.

preference.[34] Appendix E provides pump price and tax information for gasoline and noncommercial diesel fuel in the United States and various Western European countries.

Figure 3.3. 1999-2007 Average Retail Prices for Premium Gasoline and Diesel Fuel in Western European Countries and the United States (Nominal U.S. Dollars per Gallon)



Source: International Energy Agency, *Energy Prices and Taxes* (Second Quarter 2008), available by subscription or purchase from web site www.oecdbookshop.org/oecd/.

The second and more direct explanation for the relative success of light-duty diesel vehicles in Western Europe is that national governments have purposely used tax policy to favor expansion of the market for diesel vehicles. European governments have followed a pro-diesel course with the intent of using greater diesel fuel efficiency to reduce petroleum consumption.[35] Diesel engines also have garnered interest in the climate change debate, because the diesel engine's greater fuel efficiency means less petroleum usage, which translates directly into a reduction in carbon dioxide emissions.[36]

Western European governments use two different taxation methods that favor light-duty diesel vehicles over gasoline-powered alternatives: fuel taxes and vehicle taxes. Diesel fuel is taxed at a

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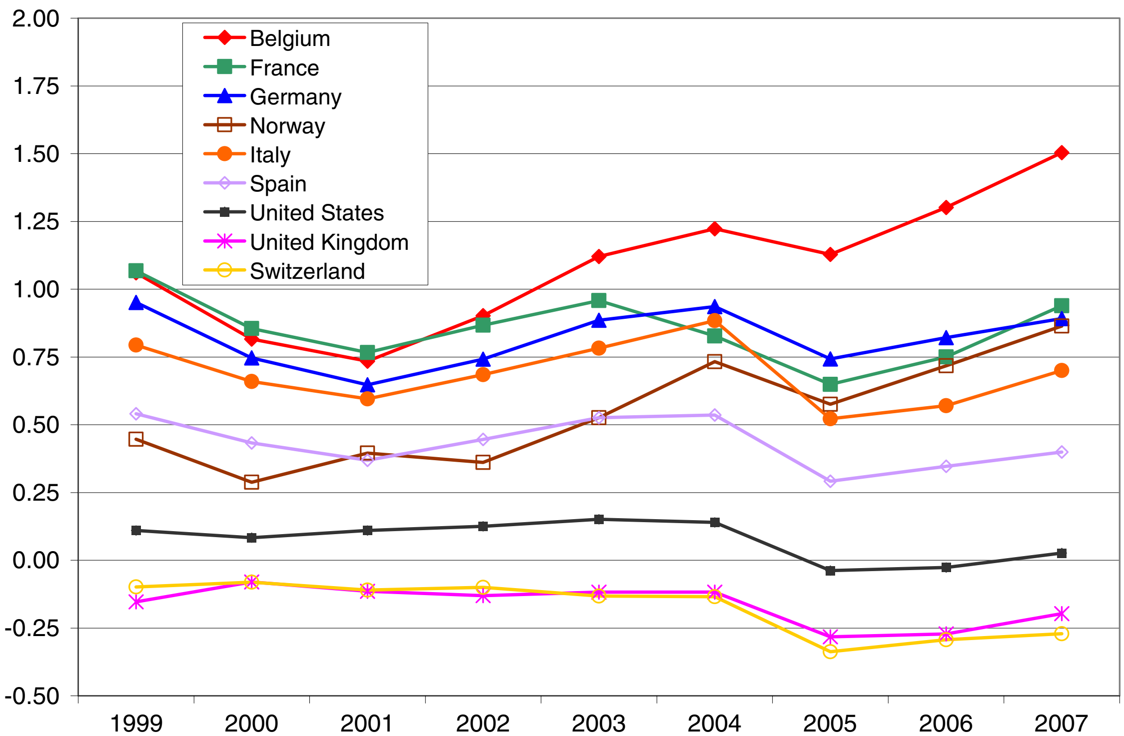
[34]International Energy Agency, *Energy Prices and Taxes* (Second Quarter 2008), available by subscription or purchase from web site www.oecdbookshop.org/oecd/. The information on Western European gasoline prices is for premium unleaded (95 RON), which is roughly equivalent to the U.S. 91octane premium unleaded grade.

[35]E.A. Taub, "Diesel Engines May Not Purr, But They Please the Mileage Mavens," *New York Times* (October 24, 2007), web site www.nytimes.com/2007/10/24/automobiles/autospecial/24audi.html; Diesel Technology Forum, *Demand for Diesels: The European Experience* (Frederick, MD, July 2001), web site www.dieselforum.org/news-center/pdfs/EuropeanExperience.pdf/at_download/file.

[36]C. Morey and J. Mark, "Diesel Passenger Vehicles—Can They Meet Air Quality Needs and Climate Change Goals?," SAE International Document No. 2000-01-1599 (April 2000), web site www.sae.org/technical/papers/2000-01-1599 (subscription site).

lower rate than gasoline in all Western European countries except Switzerland and the United Kingdom, where, coincidentally, sales of light-duty diesel vehicles are the lowest in the region (Figures 3.4 and 3.5). The lower tax rates for retail diesel fuel lead to relatively lower retail diesel fuel prices, promoting the purchase of diesel-fueled light-duty vehicles.

Figure 3.4. Average Price Difference Between Premium Gasoline and Automotive Diesel Fuel, 1999-2007 (Nominal U.S. Dollars per Gallon)



Source: International Energy Agency, *Energy Prices and Taxes* (Second Quarter 2008), available by subscription or purchase from web site www.oecdbookshop.org/oecd/. Data shown are differences between yearly average end-use prices of automotive diesel fuel for noncommercial use and 95 RON premium unleaded (Western Europe) or 91 octane premium unleaded (United States) gasoline. Positive values indicate higher prices for gasoline than for diesel; negative values indicate higher prices for diesel than for gasoline.

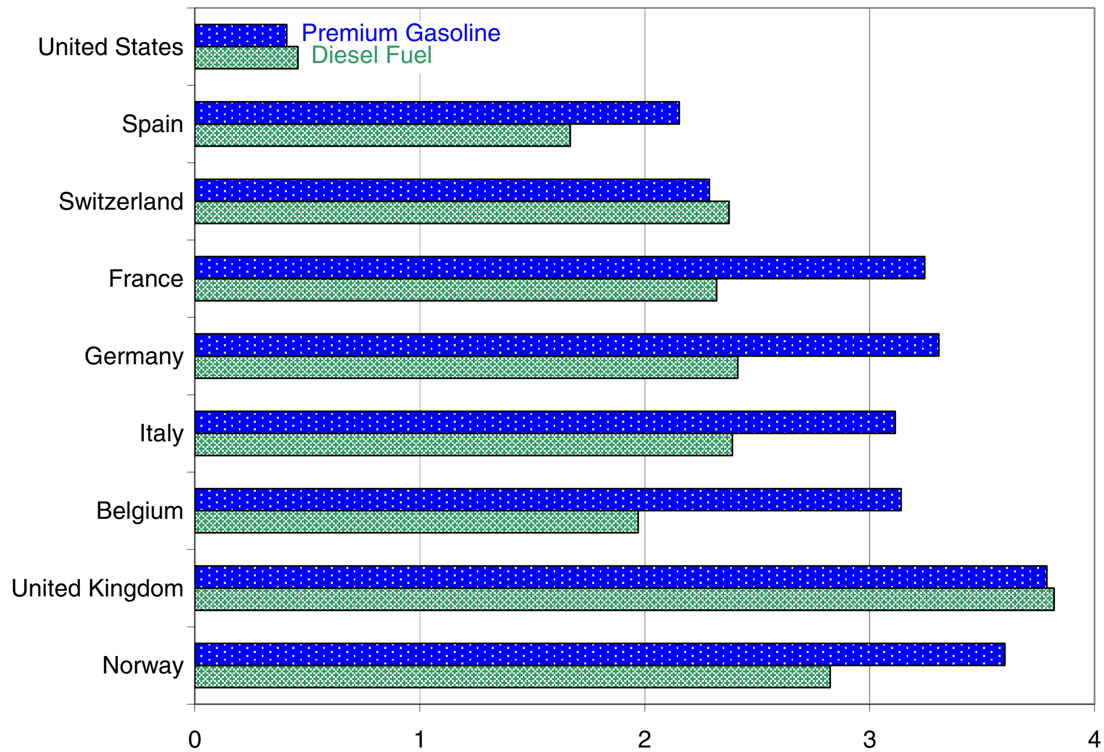
The differences between U.S. and Western European gasoline and diesel fuel taxes account for an average of 96 percent of the price difference between U.S. and European premium gasoline at the pump and 88 percent of the price difference between U.S. and Western European diesel fuel at the pump. Additionally, direct vehicle taxes and registration fees in Western Europe favor the purchase of small- and medium-class cars with diesel engines, which are subject to lower taxes in Western European countries than comparable cars with gasoline engines.[37]

The third reason that diesel engines have been more successful in penetrating the Western European light-duty vehicle fleet is that European diesel vehicle emission standards are less rigorous than those in the United States. U.S. Tier 2 standards hold both gasoline and diesel engines to the same standards for emissions of NO_x, carbon monoxide (CO), hydrocarbons (HC), and particulate matter (PM). Because diesel engines emit less CO and HC but relatively more NO_x and PM, the U.S. standard inhibits the use of diesel engines, which require more technically challenging and expensive emission control technologies. Unlike the United States, Europe has separate gasoline and

[37]U. Kunert and H. Kuhfeld, "The Diverse Structures of Passenger Car Taxation in Europe and the EU Commissions Proposal for Reform," Discussion Paper 589 (Berlin, Germany: Deutsches Institut für Wirtschaftsforschung, May 2006), web site http://ideas.repec.org/p/diw/diwwpp/dp589.html.

diesel vehicle standards, holding diesels to less stringent NO_x and PM emission requirements (Figure 3.6). The European Union will strengthen NO_x and PM standards starting in 2009, however, bringing them more in line with U.S. emissions standards. Previous European emissions standards, Euro 1 (1992) and Euro 2 (1996), regulated PM at 0.23 and 0.13 grams per mile, respectively, but did not regulate NO_x emissions.

Figure 3.5. 1999-2007 Average Tax Rates for Premium Gasoline and Diesel Fuel in Western European Countries and the United States (Nominal U.S. Dollars per Gallon)



Source: International Energy Agency, *Energy Prices and Taxes* (Second Quarter 2008), available by subscription or purchase from web site www.oecdbookshop.org/oecd/.

Impacts of Emissions Standards

To meet the U.S. Tier 2 NO_x and PM emission requirements, diesel vehicles must be equipped with various emissions-reducing technologies. Over the past 25 years, emissions of NO_x and PM from diesel vehicles have been reduced by 80 to 90 percent—impressive reductions that have been achieved almost entirely through engine design modifications.[38] Table 3.1 summarizes the various engine technologies and modifications.

Even with these engine modifications, however, several new technologies must now be added to diesel vehicles to reduce NO_x and PM even further in order to meet the EPA's latest and more stringent Tier 2 emission standards. Today, NO_x and PM emissions reduction technology is focused primarily on treating vehicle exhaust. In addition, diesel fuel sulfur levels have been drastically lowered both to reduce emissions and, more importantly, to allow new exhaust treatment equipment to function properly. Several control technologies are being tested or employed in new light-duty diesel vehicles to address PM and NO_x emissions.

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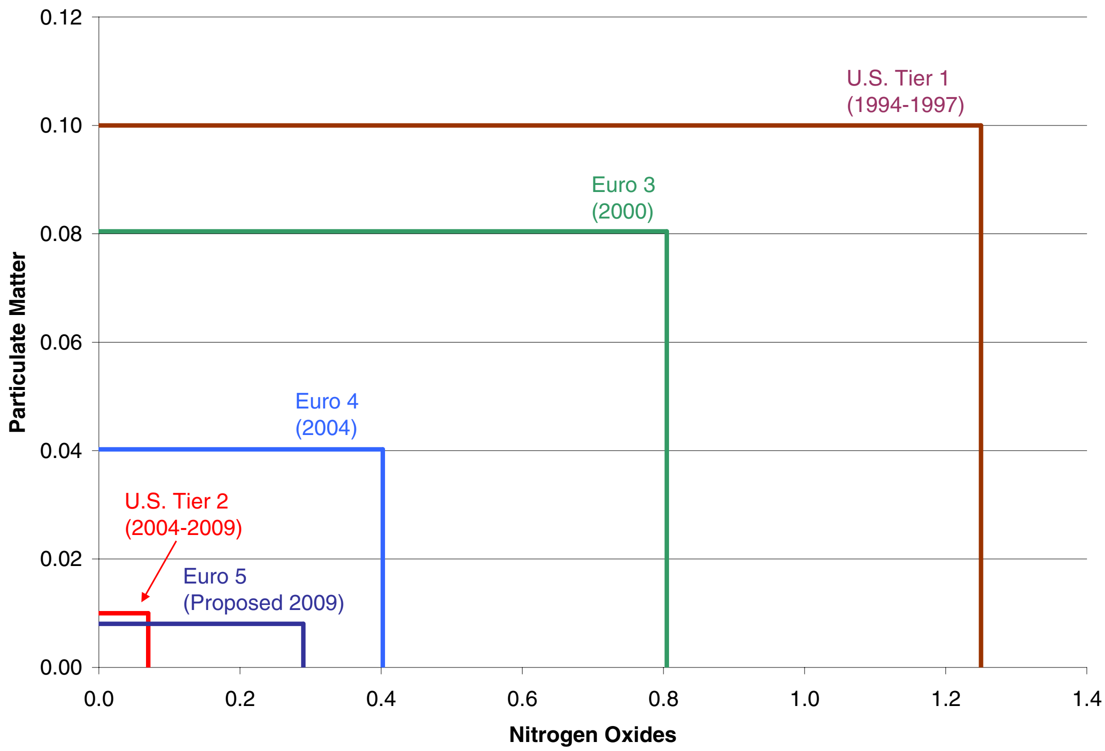
[38]C. Morey and J. Mark, "Diesel Passenger Vehicles—Can They Meet Air Quality Needs and Climate Change Goals?," SAE International Document No. 2000-01-1599 (April 2000), web site www.sae.org/technical/papers/2000-01-1599 (subscription site).

Figure 3.6. Diesel Vehicle Emissions Standards for Oxides of Nitrogen (NOx) and Particulate Matter (PM) in the United States and Western Europe (Grams per Mile)



Sources: **U.S. Tier 1:** U.S. Environmental Protection Agency, "Final Regulations for Revisions to the Federal Test Procedure for Emissions From Motor Vehicles," *Federal Register*, Vol. 61, No. 205 (October 22, 1996), web site www.epa.gov/EPA-AIR/1996/October/Day-22/pr-23769.txt.html. **U.S. Tier 2:** U.S. Environmental Protection Agency, "Control of Air Pollution From New Motor Vehicles: Tier 2 Motor Vehicle Emissions Standards and Gasoline Sulfur Control Requirements," *Federal Register*, Vol. 65, No. 28 (February 10, 2000), web site www.epa.gov/EPA-AIR/2000/February/Day-10/a19a.htm. **European Standards:** DieselNet, "Emissions Standards, European Union, Cars and Light Trucks," web site www.dieselnet.com/standards/eu/ld.php.

Table 3.1. Emissions-Reducing Modifications Made to U.S. Diesel Engines, 1980-2009

Technology	Effect on Emissions	Function
Direct Fuel Injection	Lower PM	Injects fuel and air directly into combustion cylinder, allowing for greater fuel efficiency and less emissions
Common Rail Injection	Lower PM	Dispenses fuel into cylinders at much higher pressure, allowing more complete burn of fuel
Turbocharging	Lower PM, Increased NO_x	Forces more air into combustion chamber, allowing more complete burn of fuel
Electronic Fuel Injection	Lower PM and NO_x	Calibrates air and fuel cylinder intake, allowing more complete burn and controlling temperature
Improved Combustion Chamber Configuration	Lower PM and NO_x	Achieves better air and fuel mixture in combustion cylinder, optimizing burn and temperature
Timing Injection Retard	Lower NO_x, Increases PM	Reduces cylinder temperature

Sources: Diesel Technology Forum, *Demand for Diesels: The European Experience* (Frederick, MD, July 2001), web site www.dieselforum.org/news-center/pdfs/EuropeanExperience.pdf/at_download/file; and C. Morey and J. Mark, "Diesel Passenger Vehicles—Can They Meet Air Quality Needs and Climate Change Goals?," SAE International Document No. 2000-01-1599 (April 2000), web site www.sae.org/technical/papers/2000-01-1599 (subscription site).

Particulate Matter (PM)

Diesel Particulate Filter (DPF): DPFs are filters placed into the exhaust stream to trap PM emissions before they leave the tailpipe. DPFs typically are made out of cordierite, a ceramic-like material, or silicon. DPFs force exhaust gas to pass through a series of channels containing porous filters, in the process capturing PM while allowing the remaining exhaust to pass through. DPFs capture up to 90 percent of PM emissions from passing exhaust.[39] Accumulated PM must be removed from the DPF about every 300 miles in a process known as regeneration. Regeneration is done automatically by the vehicle by increasing exhaust temperature to 550 degrees Celsius, in the process burning off the PM into small amounts of CO_2 and water.

Diesel Oxidation Catalyst (DOC): DOCs are muffler-like devices placed into the exhaust stream to reduce PM emissions. Internally, DOCs contain a honeycomb structure (substrate), which is covered with a precious metal catalytic material, typically either platinum or palladium. Exhaust gas is passed over the substrate, which causes PM to react chemically, or oxidize, with the catalytic material and break down into harmless gasses. DOCs can remove 20 to 50 percent of the PM in diesel exhaust.[40]

Oxides of Nitrogen (NO_x)

Selective Catalytic Reduction (SCR): SCR uses both a catalytic surface and a reagent to reduce vehicle NO_x emissions. First, a liquid reagent, typically urea, is sprayed into the exhaust stream before the gases reach the catalytic converter. Next, the urea mist and exhaust enter the catalyst chamber, where the mixture is chemically broken down by the catalytic material into nitrogen and water and passed out the tailpipe. Urea is important in this process because it allows the catalyst to react chemically with the vehicle's exhaust. SCR is capable of reducing NO_x emissions by up to 70 percent.[41]

Urea introduces an important complication: it must be refilled periodically. Currently, BMW, Mercedes-Benz, and Audi all use urea-based SCR technology in their diesel models, each employing a 6- to 8-gallon urea tank. If drivers fail to refill the tank, the vehicle will stop working. Manufacturers plan on making urea refill part of the vehicles' scheduled maintenance, charging about $7.75 per half-gallon bottle. There is also a desire to create an infrastructure for consumers to fill their own urea tanks, perhaps purchasing the urea at refueling stations or auto parts stores.[42] Manufacturers also plan on installing a urea warning light on the instrument panel that will alert the driver when the urea tank falls below 1 gallon of fluid. If the urea level gets critically low, a light will appear on the dashboard, indicating that the vehicle has 20 starts remaining.[43]

Exhaust Gas Recirculation (EGR): EGR is a process in which some exhaust gas is recycled from the exhaust stream back to the engine's air intake system. By combining oxygen-poor exhaust with

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[39]Manufacturers Association of Emissions Control Association, web site www.meca.org.
[40]*Ibid.*
[41]*Ibid.*
[42]G.G. Banco, "An Analysis of the Federal Government's Role in the Research and Development of Clean Diesels in the United States," SAE International Document No. 2004-01-1753 (March 2004), web site www.sae.org/technical/papers/2004-01-1753 (subscription site).
[43]T. Moran, "European Urea Diesels for U.S. Market," *Automotive News Europe* (October 27, 2008), web site www.bosch-diesel.us/pool/pdf/2008-10-27_European-urea.pdf; T. Moran, "Urea Must Flow or New Diesels Won't Go," *Automotive News* (October 20, 2008), web site www.autonews.com/article/20081020/ANA03/810200294/1186; and L. Ulrich, "Diesel Automobiles Clean Up for an Encore," *New York Times* (May 18, 2008), web site www.nytimes.com/2008/05/18/automobiles/18DIESEL.html.

fresh intake air, the oxygen level of air entering the vehicle's combustion chamber is diluted. This reduction lowers the temperature of the combustion process, which reduces the amount of NO_x emissions produced. Such EGR systems are able to reduce NO_x emissions by up to 40 percent.[44]

NO_x Catalyst Technologies: There are two NO_x catalyst technologies—lean NO_x catalyst systems and NO_x absorbers. The lean NO_x catalyst is a system similar to both DOC and SCR. Lean NO_x contains a substrate, which is covered with a catalytic material, and a liquid reagent, typically diesel fuel, introduced upstream to facilitate the oxidization of NO_x in the substrate into harmless gases. Lean NO_x differs from SCR in that it is unnecessary to introduce a second exogenous liquid (urea) to the vehicle. Lean NO_x offers up to a 25-percent reduction in vehicle NO_x emissions.[45] In an NO_x absorber, NO_x is captured by the catalyst, stored, and burned off periodically by high-temperature exhaust once the trap is saturated, similar to a DPF. NO_x absorber technology is used in the 2009 Volkswagen Diesel.[46]

Fuels

Ultra-Low-Sulfur Diesel Fuel: The most important characteristic of diesel fuel affecting emissions today is sulfur level. The sulfur level of diesel fuel is important for two reasons. First, sulfate, a sulfur-based PM, makes up a portion of total PM emitted by diesel vehicles. Roughly 1 to 2 percent of the sulfur in diesel fuel is converted to sulfate, meaning that any reduction in the sulfur content of diesel fuel will yield a corresponding reduction in PM.[47] Second, and more important, sulfur in the exhaust stream builds up on several of the vehicle's emissions after-treatment systems, especially the substrate oxidization catalysts. At first the sulfur buildup merely reduces the capability of the technologies to reduce emissions, but when enough sulfur has built up, several of the exhaust treatment devices are rendered completely ineffective. Without the exhaust after-treatment technologies working together, diesel vehicles are unable to meet the EPA Tier 2 NO_x and PM standards.

Because of sulfur's PM emissions and detrimental effect on exhaust after-treatment technology, EPA has mandated that diesel fuel sulfur levels must be reduced from 500 parts per million (ppm) to 15 ppm. Diesel fuel with a sulfur level of 15 ppm is known as ULSD. As of June 1, 2006, 80 percent of diesel fuel sold in the United States was required to be ULSD, and by December 2010 all diesel fuel sold must be ULSD.[48] The switch from low-sulfur diesel to ULSD is not without costs. Pump prices for ULSD in 2008 averaged about \$0.10 per gallon above the price of low-sulfur diesel.[49]

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[44]Manufacturers Association of Emissions Control Association, web site www.meca.org.
[45]*Ibid.*
[46]T. Moran, "European Urea Diesels for U.S. Market," *Automotive News Europe* (October 27, 2008), web site www.bosch-diesel.us/pool/pdf/2008-10-27_European-urea.pdf.
[47]C. Morey and J. Mark, "Diesel Passenger Vehicles—Can They Meet Air Quality Needs and Climate Change Goals?," SAE International Document No. 2000-01-1599 (April 2000), web site www.sae.org/technical/papers/2000-01-1599 (subscription site).
[48]U.S. Environmental Protection Agency, "Control of Air Pollution From New Motor Vehicles: Heavy-Duty Engine and Vehicle Standards and Highway Diesel Fuel Sulfur Control Requirements; Final Rule," 40 CFR Parts 69, 80, and 86, *Federal Register*, Vol. 66, No. 12 (January 18, 2001), web site www.epa.gov/EPA-AIR/2001/January/Day-18/a01a.htm.
[49]Energy Information Administration, "Petroleum Navigator: Weekly Retail Gasoline and Diesel Prices," web site http://tonto.eia.doe.gov/dnav/pet/pet_pri_gnd_dcus_nus_a.htm.

Current Market Issues

For U.S. consumers interested in purchasing a new light-duty diesel vehicle, there are few vehicles available for consideration. In the car market, Volkswagen offers diesel engines in its Jetta nameplate, Mercedes Benz offers a diesel engine in its E-Class sedan, and BMW offers a diesel in its 3 Series sedan. In the light truck segment of the market, General Motors, Ford, and Chrysler offer diesel engines in their heavy-duty pickup trucks and vans, and Mercedes Benz offers diesel engines in its R-Class, ML-Class, and GL-Class sport utility vehicles. Honda, Chrysler, and Toyota have canceled or delayed planned diesel product offerings, citing the high incremental cost of diesel fuel, costly emissions control equipment, and limited consumer interest as reasons for the decision.[50]

Although diesel vehicles are more fuel-efficient than gasoline vehicles, the current price premium for diesel fuel in the U.S. is still clearly dissuasive in terms of switching to diesel. At retail prices for diesel and gasoline ($2.27 and $1.84 per gallon, respectively, as of January 26, 2009), the efficiency of the diesel vehicle would need to be at least 23 percent higher to justify operating a light-duty diesel vehicle.[51] In addition, the spread between diesel and gasoline prices is likely to get wider, as a result of the ramping up of domestic ethanol supply and growing imports of gasoline from Europe. American refiners, historically geared heavily toward gasoline, now find that demand for gasoline in the long term is likely to diminish. Europe, while using more crude to keep up with growing diesel demand, is awash in gasoline, and the United States continues to be Europe's primary export market for excess gasoline.

Consumers also have to factor in the relatively high purchase cost of diesel vehicles relative to their gasoline-powered counterparts. Depending on the manufacturer, the incremental cost of a diesel vehicle ranges between $1,000 and $7,195, a wide range that reflects manufacturers' pricing strategies and the cost of other included equipment. The average incremental cost for a Mercedes Benz diesel vehicle is $1,250; the average for a Volkswagen or BWM diesel is $4,225; and the average for a diesel-powered heavy pickup truck is $6,730. Offsetting some or all of these costs is the fact that diesel vehicles are also eligible for tax credits ranging from $900 to $1,800, depending on the vehicle.[52] Mercedes Benz has priced its diesel vehicles so that their incremental cost is equal to the available tax credit.

In addition to the economic hurdles faced by diesel vehicles, consumers also associate problems with diesel vehicles from the 1980s with the advanced diesel vehicles offered today. A recent survey measuring willingness to purchase diesel vehicles indicated that fewer than 15 percent of consumers would consider diesel as an acceptable option for their next vehicle purchase. In contrast, 70 percent said they would consider a hybrid vehicle.[53] In another survey, which asked consumers why they would not consider a diesel vehicle, vehicle noise, smell or odor, price, maintenance cost, pollution, and cold start problems were cited by the respondents.[54] In addition to consumer opinions about

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[50]See web site http://wardsauto.com (subscription site): **Chrysler:** E. Mayne, "Bluetec Grand Cherokee Rollout on Rocks" (September 10, 2008); **Toyota:** E. Mayne, "Diesel-Powered Tundra Under Review" (October 1, 2008); **Honda:** C. Schweinsberg, "Honda Cancels Acura Diesel" (October 30, 2008).
[51]Energy Information Administration, "Petroleum Navigator: Weekly Retail Gasoline and Diesel Prices," web site http://tonto.eia.doe.gov/dnav/pet/pet_pri_gnd_dcus_nus_a.htm.
[52]26 U.S. Code 30B, "Alternative Motor Vehicle Credit." See web site www.irs.gov/businesses/article/0,,id=175456,00.html.
[53]Opinion Research Corporation International for the National Renewable Energy Laboratory, Study No. 717318 (July 31-August 3, 2008).
[54]Opinion Research Corporation International for the National Renewable Energy Laboratory, Study No. 70627 (July 3, 1997).

diesel vehicles, 63 percent also considered the availability of diesel fuel to be a problem.[55] Although many of these perceptions are no longer accurate, they present a market issue that must be addressed before widespread consumer acceptance of diesel vehicles can be achieved.

Higher vehicle costs, coupled with higher prices for diesel fuel, constitute an economic disincentive for purchases of diesel vehicles. Thus, other attributes of diesel vehicles—such as durability, longevity, and power output—are likely to provide the justification for decisions to purchase diesel vehicles despite the additional expense. Consumers who have high travel requirements may choose diesel vehicles for their durability and longevity, and those who use their vehicles often for hauling or towing heavy loads may choose diesels for their superior power output.

[55]Opinion Research Corporation International for the National Renewable Energy Laboratory (May 20-23, 2004).

4. Fuel Quality and Availability

Given the recent but consistent differences in diesel prices relative to gasoline prices, consumer interest in light-duty diesel vehicles may be influenced by expectations of a continued large price premium for diesel fuel. The recent premium can for the most part be attributed to an imbalance of supply and demand for the two fuels both in the United States and abroad. In particular, the growth of diesel demand and decline in gasoline demand in Europe, which exports much of its excess gasoline to the United States, has kept and will continue to keep pressure on the price differential between diesel fuel and gasoline.

Until 2005, gasoline prices usually were higher during the summer months as a result of higher demand associated with the summer driving season, whereas diesel prices typically were higher during the fall and winter months because of demand for heating oil and diesel use in farm equipment for harvesting. In 2005, a tightening of the distillate market,[56] coupled with a loosening of the gasoline market, especially within the Atlantic Basin (i.e., the United States and the European Union), was becoming apparent. The growing market shifts led to a large and persistent price differential. Some of the diesel price premium can be attributed to costs associated with the transition to ULSD for highway freight fuel here in the United States, especially from 2005 to 2006, when the transition to cleaner diesel was just beginning.[57] As detailed below, however, it is the increasing demand for distillate *relative to* demand for gasoline that plays the major role in determining the price differential.

Although the price impact of growth in distillate demand relative to gasoline demand was not reflected in retail prices until 2005, worldwide supply and demand imbalances had been occurring before 2005 (Figure 4.1). A major contributor to the growth in world distillate demand has been increased consumption in developing nations. For example, the power industry in South America (in particular, Chile, where a drought has curtailed hydropower output) has recently increased its reliance on diesel fuel.[58] China also has seen a dramatic increase in distillate demand (accompanied by an increase in diesel imports) as a result of its rapid economic growth in recent years and its buildup of distillate stocks in preparation for the 2008 Olympics. In India, where there is an effort to boost refining capacity, distillate supplies will continue to be tight in the near term because of the large growth in electric power demand, which in the face of limited growth in refining capacity growth has led to growing use of small generators that burn diesel fuel.[59]

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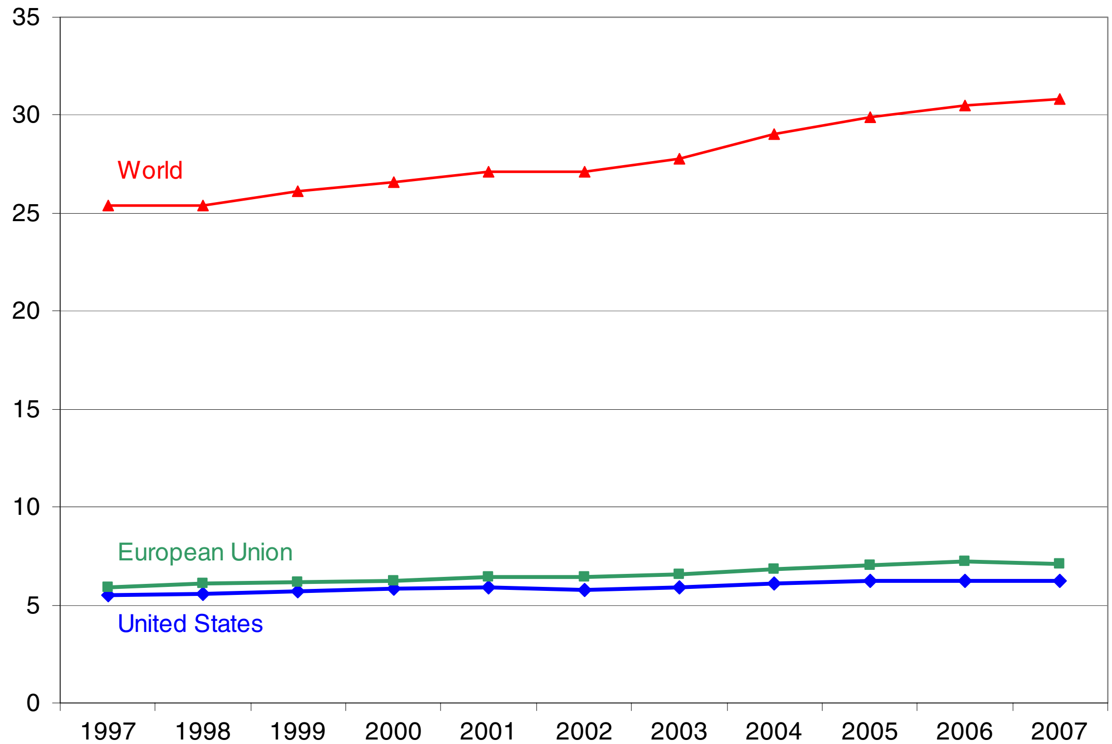
[56]Diesel fuel is part of a more general product slate called "distillates," which includes off-road diesel, gasoil, heating oil, and kerosene.

[57]Diesel production has undergone dramatic changes in the past few years with respect to environmental specifications as well as production output technologies and continues to evolve both in the United States and abroad. Specifically, diesel desulfurization efforts took a dramatic turn in 2006 with the implementation of the Clean Air Act Amendments of 1990 (see web site www.epa.gov/air/caa/caaa.txt) in a major effort to reduce air pollution and acid rain. Between 1993 and 2006, U.S. highway diesel could contain up to 500 ppm sulfur concentration. With the exception of small refineries (those with a distillation capacity of less than 155,000 barrels per day), starting on June 1, 2006, 80 percent of highway diesel fuel marketed by producers and importers was required to be ULSD with a concentration of 15 ppm or less. By December 1, 2010, all highway diesel fuel sold at U.S. retail outlets must be ULSD. In addition, the EPA also promulgated a timeline for the desulfurization of non-road, locomotive, and marine diesel fuel, which by 2014 must also be ULSD.

[58]The U.S. refining industry has in recent years sought to export product there, thus keeping the distillate supply tight in the U.S. market and, in turn, keeping diesel margins high. See W. Pentland, "America's Oil Export Problem (Yes, Export)," web site www.forbes.com/2008/09/30/energy-diesel-exports-biz-energy-cx_wp_1001energy08_exports.html.

[59]J. Vautrain, "Special Reports: China, India Lead Growth in Asian Refining Capacity," *Oil and Gas Journal*, Vol. 106, No. 47 (December 15, 2008), web site www.ogj.com/articles/save_screen.cfm?ARTICLE_ID=347791.

Figure 4.1. Middle Distillate Consumption by Region, 1997-2007 (Million Barrels per Day)



Source: BP p.l.c., *BP Statistical Review of World Energy June 2008* (London, UK, 2008), web site www.bp.com/productlanding.do?categoryId=6929&contentId=7044622.

Increased distillate demand in the United States is correlated with economic growth and the associated increase in freight traffic. More significant, however, is the fact that U.S. distillate demand has been increasing at a faster rate than motor gasoline demand since 2002, as evidenced by highway diesel consumption that grew by about 3 percent per year from 2002 to 2007 (overall distillate demand grew by 2 percent per year) while gasoline consumption grew by 1 percent per year.[60]

The U.S. refining industry has tried to keep pace with the shift in petroleum product demand. From 2002 to 2007, net production of distillate fuel by domestic refineries and blenders increased by 15 percent, while production of highway diesel fuel increased by more than 33 percent.[61] The growth in production was only slightly higher than the increase in demand for distillate and diesel fuel over the same period. U.S. refineries have adapted to the shift in product demand by producing more distillate and less gasoline—mostly through operational changes, as opposed to major plant additions. From 2002 to 2007, the yield of gasoline products fell by more than 2 percent, while the yield of distillate products increased by almost 3 percent.[62]

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[60]American Petroleum Institute, "Why Recent Retail Diesel Prices Have Been Higher Than Gasoline Prices" (January 16, 2009), web site www.api.org/aboutoilgas/diesel/upload/January-2009_high_retail_diesel_prices.pdf.

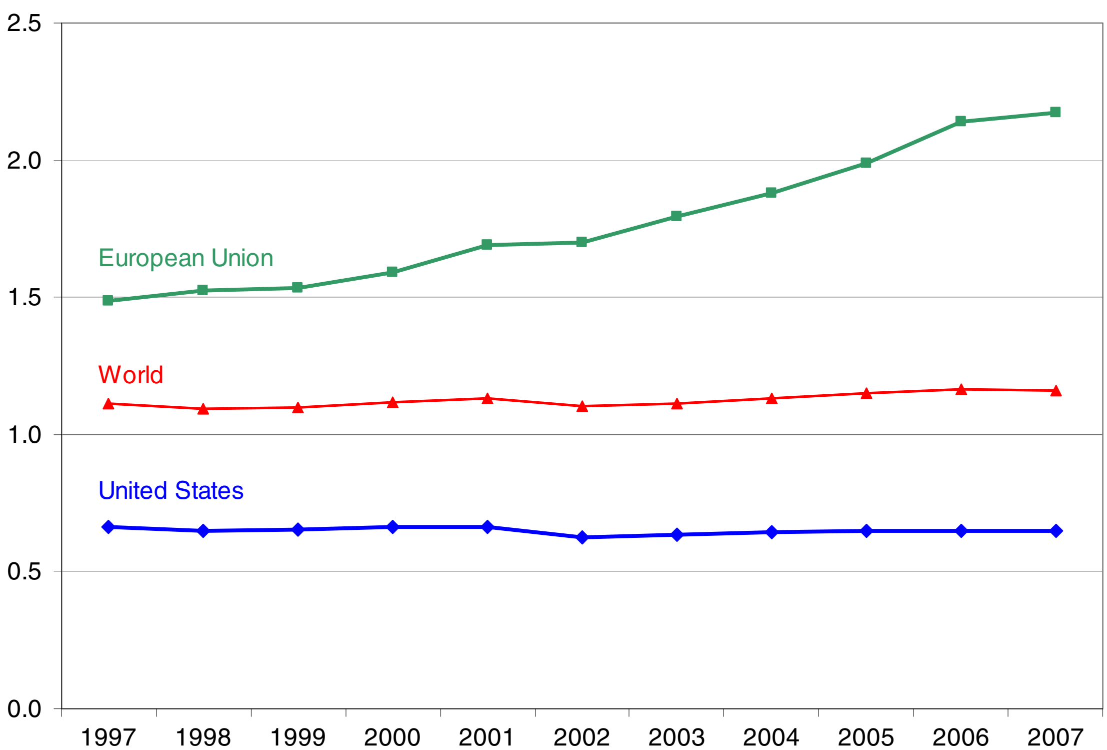
[61]Energy Information Administration, Form EIA-810, "Monthly Refinery Report," and Form EIA-815, "Monthly Terminal Blenders Report," web site http://tonto.eia.doe.gov/dnav/pet/pet_pnp_refp_dc_nus_mbbl_a.htm.

[62]Energy Information Administration, "Petroleum Navigator: Refinery Yield," web site http://tonto.eia.doe.gov/dnav/pet/pet_pnp_pct_dc_nus_pct_a.htm.

The shift in product yield has allowed U.S. refiners to meet growing distillate demand without relying solely on increasing the amount of crude oil throughput. As a result, many refineries have been able to take economic advantage of the growing demand for diesel in recent years. The relative shortage of production capacity, however, has put strain on the refining industry.[63] U.S. gasoline production has increased by about 3 percent over the same period, and to meet the 5-percent growth in gasoline demand over the period, motor gasoline imports, in particular from Europe, have been increasing. Europe's increasing ability to supply (and, in the future, perhaps to oversupply) the North American gasoline market is a key factor in the price differential between diesel and motor gasoline.

The most prominent force in changing the dynamics of petroleum product markets has been growing demand for diesel fuel to supply the growing diesel component of the European Union's light-duty vehicle fleet, which together with declining demand for gasoline in Europe has led to a tighter diesel market and a looser gasoline market in the Atlantic Basin. The shift in the European transportation fuel market is illustrated in Figure 4.2, which shows the rapidly increasing consumption of diesel relative to gasoline. Since 1997, demand for diesel fuel and heating oil has increased by 15 percent, while demand for gasoline has fallen by 22 percent.[64]

Figure 4.2. Ratio of Middle Distillate Consumption to Consumption of Gasoline and Light Naphtha Products by Region, 1997-2007



Source: BP p.l.c., *BP Statistical Review of World Energy June 2008* (London, UK, 2008), web site www.bp.com/productlanding.do?categoryId=6929&contentId=7044622.

With refineries in Western Europe struggling to keep up with diesel demand, European imports of diesel fuel are on the rise. In fact, the International Energy Agency (IEA) projects that, despite efforts to expanded middle distillate production capacity, Western Europe will remain a net importer

[63] A. Campoy, "Refiners Tilt to Diesel Over Gasoline," *Wall Street Journal* (May 16, 2008), web site http://online.wsj.com/article/SB121090017595697445.html.
[64] *Diesel Fuel News* (April 4, 2008).

of diesel at least through 2013.[65] On the other hand, limitations on refinery yield have created an excess of lighter naphtha products and gasoline in Western Europe. The United States has served as a large export market for the excess gasoline, as evidenced by an increase in net imports of motor gasoline (finished and blending components) from 335 thousand barrels per day in 2004 to 559 thousand barrels per day in 2007.[66]

In the future, the supply imbalance for petroleum products, especially in the Atlantic Basin, may continue to exacerbate the diesel price premium. Worldwide, distillate supplies are likely to remain tight for some time, and Europe is likely to continue importing distillate well into the future (although some additional supply should become available as refining capacity both in Asia and the Middle East continues to grow).[67] At the same time, the Atlantic Basin probably will continue to be awash in gasoline from European refineries, thereby continuing to put downward pressure on U.S. gasoline prices.

Petroleum distillate demand in the United States is also expected to grow in the medium to long-term, while petroleum gasoline demand is expected to fall (Table 4.1). The expected decline in gasoline demand would be driven largely by more stringent CAFE standards and mandated use of biofuels, particularly ethanol, which displaces motor gasoline. The opposing demand trends could support or even increase the diesel price premium well into the future.

Table 4.1. Projected Shift in U.S. Consumption of Petroleum-Based Gasoline and Distillate Fuels, 2007-2030 (Million Barrels per Day)

	2007	2030	Growth, 2007-2030
Petroleum Gasoline[a]	8.84	7.92	-0.92
Petroleum Diesel[b]	4.16	4.80	0.64

[a]"Petroleum Gasoline" refers to motor gasoline, excluding ethanol components.
[b]"Petroleum Diesel" refers to diesel minus any distillate stream from alternative fuels (BTL, CTL, GTL, green diesel, biodiesel, etc.).
Source: Energy Information Administration, *AEO2009* Early Release Reference Case (December 17, 2008).

In Europe, biofuel production is geared more toward biodiesel than ethanol, which is consistent with the expected long-term growth in product demand. In the short term, however, the IEA projects that biodiesel consumption will reach only about 1 percent of global gasoil consumption by 2012,[68] and

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[65]International Energy Agency, *Medium Term Oil Report* (July 2008), web site http://omrpublic.iea.org/mtomr.htm (subscription site).
[66]Energy Information Administration, Form EIA-814, "Monthly Imports report," U.S. Imports of Motor Gasoline Blending Components, web site http://tonto.eia.doe.gov/dnav/pet/pet_move_impcus_a2_nus_epobg_im0_mbbl_m.htm.
[67]In Europe, highway diesel fuel must meet the Euro 5 (10 ppm) sulfur standards by January 1, 2009. Many countries in Asia also are moving toward production of ULSD because of public health considerations, while refiners in the Middle East are also moving toward the Euro 5 highway diesel fuel sulfur standards, in part because they see Europe as an attractive diesel export market both in the near and long term. How quickly refineries abroad, especially in Asia, are able to ramp up distillate capacity and implement clean diesel technology will influence the length of time developed nations like the United States will continue to experience relatively high diesel prices. The ability of foreign suppliers to act in the short term could be hindered by price controls on diesel products in those countries that would in effect discourage refiners from making upgrades. See: Asian Development Bank, *A Roadmap for Cleaner Fuels and Vehicles in Asia* (November 2008), web site www.cleanairnet.org/caiasia/1412/articles-71194_roadmap.pdf.
[68]International Energy Agency, *Medium Term Oil Report* (July 2008), web site http://omrpublic.iea.org/mtomr.htm (subscription site).

it is widely agreed that the incremental increases in biodiesel production both in Europe and elsewhere will continue to be small relative to the growing demand for distillate fuel.[69, 70]

Although much of the projected increase in U.S. distillate demand is expected to continue to be met with operational changes at U.S. refineries, many refiners have also expressed optimism about a host of technologies involving new diesel catalysts[71] that will further increase diesel yields, as well as the use of specialized cokers to upgrade heavy bunker fuel efficiently to diesel fuel.[72] Given the expected increases in future distillate demand, as well as the long-term potential profitability of diesel relative to gasoline, some refiners are making concerted investments in boosting diesel production. Some current refinery expansions are geared toward producing more diesel fuel. For example, Marathon's refinery in Garyville, Louisiana, includes the addition of a 180,000-barrel-per-day hydrocracker, and Motiva's large expansion of its Port Arthur refinery[73] will allow for greater flexibility in switching from light product (gasoline blending components) to diesel. In addition, ExxonMobil recently announced that it would invest more than $1 billion to increase its global diesel production by 10 percent.[74]

As a whole, the role of alternative fuels in relieving tight distillate markets in the future may be limited. Biodiesel, made from soybean oil or grease feedstocks, is not completely fungible with petroleum diesel, and its content in diesel fuel is often limited to 5 percent (7 percent in Europe). Renewable diesel, which is created by hydrogenating vegetable oil, is completely fungible with petroleum diesel. BTL fuels (which EIA projects to grow to 5 billion gallons per year of domestic production by 2030) are created via the same Fischer-Tropsch process used to make CTL fuel, and they also are completely fungible with petroleum-based diesel. Biodiesel production, however, has a much lower capital cost, because renewable diesel production requires the acquisition or production of hydrogen gas, and BTL production requires a gasification reactor. Thus, biodiesel is more prevalent.

In the United States, the Energy Independence and Security Act of 2007 mandates consumption of 0.5 billion gallons of biodiesel in 2009 and 1.0 billion gallons in 2012 and thereafter. Renewable diesel, for which there is no specific mandate, can be used to meet part of the overall requirement for advanced biofuels, and BTL counts toward the cellulosic portion of the renewable fuels mandate. Although biofuels could make a significant contribution to diesel supplies, there is significant uncertainty about the capital and variable costs of renewable fuels projects; and because refinery investments require long lead times and planning, their impact may not be realized for many years. In addition, the future of biofuels is vulnerable to sustainability issues with regard to land use and the potential displacement of food crops. CTL and GTL production of diesel fuel also could help to alleviate diesel supply issues, but the future of CTL is highly speculative, given the capital-intensive nature of CTL projects, their significant GHG emissions and other environmental concerns, their low energy efficiencies, and their water use.

Another issue of particular importance to future distillate supplies is marine bunker fuel regulations mandated by Annex VI of the International Convention for the Prevention of Pollution from Ships

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[69] Organization of the Petroleum Exporting Countries, *World Oil Outlook 2008* (Vienna, Austria, 2008), web site www.opec.org/library/world%20oil%20outlook/WorldOilOutlook08.htm.
[70] International Energy Agency, *World Energy Outlook 2008*. (London, UK, November 2008), web site www.worldenergyoutlook.org.
[71] *Diesel Fuel News* (November 10, 2008).
[72] *Diesel Fuel News* (September 1, 2008).
[73] *World Refining and Fuels Today* (December 11, 2007).
[74] A. Campoy, J. Resnick-Ault, and R. Gold, "Refiners Cut Back on Gasoline," *Wall Street Journal* (December 17, 2008), web site http://online.wsj.com/article/SB122947423155012413.html.

(MARPOL).[75] The key goal of the Annex VI amendments is to set a timeline for the reduction of sulfur in marine fuels.[76] The current global limit for sulfur content in marine bunker fuel is 4.5 percent, and the treaty mandates that the limit be reduced to 3.5 percent in 2012 and 0.5 percent by 2020 or 2025, depending on the future feasibility of obtaining the goal. In addition, there is a provision for Sulfur Emission Control Areas, which are coastal areas, often near populous ports, where even more stringent sulfur limits can be applied. The United States is a signatory to the 1997 MARPOL Annex VI international agreement, including the amendments ratified in 2008.

Lowering the sulfur content of bunker fuel would necessitate either the use of desulfurized marine diesel and gasoil as ship fuel or a massive investment by shippers in exhaust scrubbers to continue using high-sulfur marine bunker fuel. Given the tightening supply of diesel, potential new demand for more diesel to fuel marine freight travel would bring additional pressure on diesel supplies, further increasing the price differentials between distillate and other petroleum fuels. In addition, although marine bunker fuel makes up less than 5 percent of total global petroleum product consumption, it nevertheless has served as an important market for high-sulfur heavy residual fuels. One potential solution would be for refiners to invest in heavy residual conversion projects to break down residual oil into middle distillates. The capital and operating costs associated with such conversion projects would be high, however, and they would be passed on to ship operators. As a result, the ultimate affect of the MARPOL agreement on diesel supply is uncertain.

Finally, the possibility of a low-carbon fuel standard (LCFS), currently being considered in California, could provide a price advantage for diesel fuel.[77] From a refiner's perspective, production of diesel fuel may have an advantage within a carbon tax or a cap-and-trade regulatory framework. For example, a 2005 study of the European refining industry[78] demonstrated that, on average, refineries producing diesel emitted about one-half the CO_2 emitted by refineries producing naphtha/gasoline streams. Because European refineries are configured somewhat differently from their American counterparts (to produce more distillate), GHG emissions in the processing may be different; however, given the savings in GHG emissions from diesel refining and vehicle operations described above, a national LCFS framework probably would narrow the price differential between diesel fuel and gasoline and provide incentives for diesel car purchases.

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[75]See, for example, J.E. McCarthy, *Air Pollution from Ships: MARPOL Annex VI and Other Control Options*, Order Code RL34548 (Washington, DC: Congressional Research Service, updated September 9, 2008), web site http://ncseonline.org/nle/crsreports/08July/RL34548.pdf.
[76]J. Vautrain, "New Regs Require Lower Bunker Fuel Sulfur Levels," *Oil and Gas Journal*, Vol. 106, No. 44 (November 24, 2008), web site www.ogj.com/articles/save_screen.cfm?ARTICLE_ID=346119.
[77]California Air Resources Board, *The California Low Carbon Fuel Standard Regulation: Draft* (December 2008), web site www.arb.ca.gov/fuels/lcfs/1208lcfsreg_draft.pdf.
[78]J. Reinaud, *The European Refinery Industry Under the EU Emissions Trading Scheme* (Paris, France: International Energy Agency, November 2005), web site www.iea.org/Textbase/Papers/2005/IEA_Refinery_Study.pdf.

Appendix A. Analysis Request Letter

JEFF SESSIONS
ALABAMA

COMMITTEES:
ARMED SERVICES
JUDICIARY
ENERGY AND NATURAL RESOURCES
BUDGET

United States Senate

WASHINGTON, DC 20510–0104

October 17, 2008

The Honorable Samuel Bodman
Secretary
U.S. Department of Energy
1000 Independence Avenue, SW
Washington, DC 20585

Dear Secretary Bodman:

Currently, diesel refined from crude oil is the most widely used transportation fuel in the world. Diesel fuel is critically important to America's economy. Nearly all trucks, delivery vehicles, buses, trains, ships, boats and barges, farm, construction and military vehicles and equipment have diesel engines. What's more, the price of diesel fuel affects the cost of food because nearly everything we buy in the supermarket is shipped across the country by trucks.

Diesel fuel is more efficient than other fuels. According to Popular Mechanics, the next generation of clean diesel vehicles runs approximately 38 percent farther on a gallon of fuel than similar hybrid models. The magazine found that a 2007 Volkswagen Polo Bluemotion diesel automobile travels farther on a gallon of fuel than a 2007 Toyota Prius hybrid. VW model also emits 5% fewer greenhouse gases per mile than the Toyota. Diesel vehicles also last longer than gasoline-powered vehicles. In addition to being fuel efficient, diesel-powered vehicles release fewer CO_2 emissions than similar hybrids and gasoline engines. According to the Popular Mechanics field test, the VW model tested by the magazine emits 5% fewer greenhouse gases per mile than a Toyota Prius.

Diesel vehicles run on ultra-low sulfur diesel that is 97% cleaner than older diesel fuel. New diesel technology also reduces carbon monoxide, nitrogen oxide, and other particulate emissions levels. According to the Environmental Protection Agency, if 33 percent of American drivers switched to diesel vehicles, oil consumption in the United States would be reduced by approximately 1.5 million barrels of oil a day, which could cut imports by an estimated 10%.

Yet despite these attributes diesel vehicles are not widely available in the U.S. According to the automotive consulting firm R.L. Polk & Company, only approximately 3.5% of automobiles sold in the U.S. are diesel. In Europe, approximately 50% of automobiles sold are diesel. Currently, the U.S. fleet of refineries is geared to produce gasoline.

I am thus writing to request that the Energy Information Administration (EIA) analyze the environmental and energy efficiency attributes of diesel fuel. Specifically, I would like to know how diesel fueled vehicles compare to similar gasoline fueled, E-85 fueled, and hybrid vehicles. Are they more fuel efficient? Do they emit less carbon dioxide? When and how was the decision made in this country to rely primarily on gasoline as a transportation fuel instead of diesel? Who made this decision? What are the technical, economic, regulatory, environmental, or other obstacles to increasing the usage of diesel fueled vehicles? Does the Department of Energy have any recommendations relating to whether or not we should have more diesel cars in our fleet?

I appreciate your consideration of my request, and I look forward to your timely response. Please do not hesitate to contact me or James Wallner, of my staff, at (202) 224-3972 should you have any questions.

Very Truly Yours

Jeff Sessions
United States Senator

Cc: the Honorable Howard Gruenspecht
Lisa Epifani

Appendix B. GREET Greenhouse Gas Emissions and Fuel Economy Projections for Various Vehicle Types, 2010

Table B.1. Passenger Car Emissions and Fuel Economy by Vehicle Type

Vehicle Type	Fuel Economy		Greenhouse Gas Emissions (grams per mile)				
	Miles per Gallon	Percent Difference from Diesel	Feedstock	Fuel	Vehicle Operation	Total	Percent Difference from Diesel
Diesel	28.2		30	45	330	405	
Diesel with B20	28.2	0	-9	12	331	334	-18
Conventional Gasoline (Corn E10)	23.5	-17	18	74	384	476	18
Flex Fuel with Corn E85	23.5	-17	-178	190	377	389	-4
Flex Fuel with Cellulosic E85	23.5	-17	-221	15	377	171	-58
Hybrid Electric Vehicle (Grid Independent-Corn E10)	34.8	23	12	50	260	322	-20
Hybrid Electric Vehicle (Grid Independent-Corn E85)	34.8	23	-121	128	256	263	-35
Hybrid Electric Vehicle (Grid Independent-Cellulosic E85)	34.8	23	-150	10	256	116	-71
Hybrid Electric Vehicle (Grid Independent Diesel Fuel)	34.8	23	23	34	248	305	-25
Hybrid Electric Vehicle (Grid Independent-B20)	34.8	23	-2	-17	249	230	-43
Plug-In Hybrid Electric Vehicle (US Grid-Corn E10)	41.8	48	16	150	174	340	-16
Plug-In Hybrid Electric Vehicle (US Grid-Corn E85)	41.8	48	-73	203	172	302	-25
Plug-In Hybrid Electric Vehicle (US Grid-Cellulosic E85)	41.8	48	-92	123	172	203	-50
Plug-In Hybrid Electric Vehicle (US Grid-Diesel Fuel)	44.4	57	23	139	166	328	-19
Plug-In Hybrid Electric Vehicle (US Grid-B20)	44.4	57	7	105	167	279	-31
Plug-In Hybrid Electric Vehicle (Northeast Grid-Corn E10)	41.8	48	16	122	174	312	-23
Plug-In Hybrid Electric Vehicle (Northeast Grid-Corn E85)	41.8	48	-73	175	172	274	-32
Plug-In Hybrid Electric Vehicle (Northeast Grid-Cellulosic E85)	41.8	48	-93	96	172	175	-57
Plug-In Hybrid Electric Vehicle (Northeast Grid-Diesel Fuel)	44.4	57	23	112	166	301	-26
Plug-In Hybrid Electric Vehicle (Northeast Grid-B20)	44.4	57	6	78	167	251	-38
Plug-In Hybrid Electric Vehicle (California Grid-Corn E10)	41.8	48	16	99	174	289	-29
Plug-In Hybrid Electric Vehicle (California Grid-Corn E85)	41.8	48	-73	151	172	250	-38
Plug-In Hybrid Electric Vehicle (California Grid-Cellulosic E85)	41.8	48	-93	72	172	151	-63
Plug-In Hybrid Electric Vehicle (California Grid-Diesel Fuel)	44.4	57	23	88	166	277	-32
Plug-In Hybrid Electric Vehicle (California Grid-B20)	44.4	57	6	54	167	227	-44

Source: Results taken from the Argonne National Laboratory's Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model, Version 1.8b.

Appendix C. GREET Electricity Generation Mix for Transportation Use

Table C.1. Electricity Generation for Transportation by Fuel

Fuel	U.S. Mix	Northeast U.S. Mix	California Mix
Residual Oil	2.7%	6.6%	0.7%
Natural Gas	18.9%	20.9%	41.5%
Coal	50.7%	32.2%	14.6%
Nuclear Power	18.7%	31.0%	18.9%
Biomass	1.3%	3.6%	1.7%
Other	7.7%	5.7%	22.6%

Source: Results taken from the Argonne National Laboratory's Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model, Version 1.8b.

Appendix D. Shares of New Light-Duty Diesel Vehicles Sold in U.S. and Western European Markets

Table D.1. Percent Shares of New Light-Duty Diesel Vehicles Sold, 1999-2007

Year	United States	Western Europe	Belgium	France	Germany	Italy	Norway	Spain	Switzerland	United Kingdom
1999	2.9	28.4	54.3	44.1	22.4	29.1	8.2	51.7	6.6	13.8
2000	2.5	32.3	56.7	49.0	30.4	33.7	9.0	53.1	9.2	14.1
2001	2.8	36.0	62.6	56.2	34.6	36.6	13.3	52.5	13.3	17.8
2002	2.7	40.4	64.2	63.2	38.0	43.6	17.5	57.3	17.8	23.5
2003	2.6	43.6	68.3	67.4	39.8	48.7	23.2	60.4	21.5	27.3
2004	3.2	48.3	69.9	69.2	44.0	58.4	27.0	65.1	25.9	32.5
2005	2.3	49.4	72.6	69.1	42.7	58.5	39.2	67.7	28.1	36.8
2006	2.3	51.0	74.7	71.4	44.3	58.2	48.4	70.0	30.0	38.3
2007	1.8	52.2	76.4	73.6	46.8	55.3	73.4	70.0	30.9	38.7

Sources: S.C. Davis, S.W. Diegel, and R.G. Boundy, Transportation Energy Data Book: Edition 27, ORNL-6981 (Oak Ridge, TN, 2008), web site http://cta.ornl.gov/data/index.shtml, Tables 4-5 and 4-6; and AID Ltd, *AID Newsletter*, Nos. 0102, 0302, 0501, 0602, 0702, and 0714 (2001-2007), web site www.eagleaid.com/index.htm (subscription site).

Appendix E. Yearly Gasoline and Noncommercial Diesel Fuel Prices and Tax Rates

Table E.1. Retail Pump Prices for Gasoline (U.S. 87 and 91 Octane, Western Europe 95RON) and Noncommercial Diesel Fuel and Tax Rates, by Country, 1999-2007
(2007 U.S. Dollars)

United States

Year	Unleaded Gasoline (87 Octane)	Premium Gasoline (91 Octane)	Diesel Fuel	Gasoline Tax (Federal + Average State)	Diesel Fuel Tax (Federal + Average State)
1999	1.14	1.23	1.12	0.38	0.44
2000	1.48	1.58	1.50	0.38	0.45
2001	1.42	1.51	1.40	0.38	0.45
2002	1.35	1.44	1.32	0.39	0.45
2003	1.56	1.66	1.51	0.39	0.45
2004	1.85	1.95	1.81	0.39	0.45
2005	2.27	2.37	2.41	0.39	0.46
2006	2.57	2.68	2.70	0.48	0.49
2007	2.80	2.91	2.88	0.50	0.50

Belgium

Year	Premium Gasoline (95 RON)	Diesel Fuel	Gasoline Tax	Diesel Fuel Tax
1999	3.64	2.58	2.68	1.62
2000	3.65	2.83	2.40	1.50
2001	3.26	2.53	2.21	1.38
2002	3.49	2.59	2.42	1.54
2003	4.35	3.23	2.93	1.82
2004	5.37	4.14	3.54	2.27
2005	6.02	4.89	3.81	2.49
2006	6.43	5.12	3.93	2.46
2007	7.18	5.67	4.36	2.66

France

Year	Premium Gasoline (95 RON)	Diesel Fuel	Gasoline Tax	Diesel Fuel Tax
1999	3.84	2.77	3.03	2.01
2000	3.80	2.95	2.66	1.83
2001	3.35	2.59	2.40	1.64
2002	3.62	2.75	2.67	1.82
2003	4.35	3.39	3.23	2.23
2004	4.99	4.16	3.59	2.64
2005	5.46	4.81	3.66	2.75
2006	5.88	5.12	3.76	2.82
2007	6.60	5.66	4.21	3.14

Germany

Year	Premium Gasoline (95 RON)	Diesel Fuel	Gasoline Tax	Diesel Fuel Tax
1999	3.52	2.57	2.60	1.73
2000	3.54	2.79	2.45	1.70
2001	3.31	2.66	2.37	1.69
2002	3.74	3.00	2.74	1.98
2003	4.68	3.79	3.45	2.53
2004	5.34	4.41	3.82	2.82
2005	5.75	5.01	3.87	2.90
2006	6.12	5.30	3.96	2.96
2007	6.95	6.06	4.51	3.41

Italy

Year	Premium Gasoline (95 RON)	Diesel Fuel	Gasoline Tax	Diesel Fuel Tax
1999	3.87	3.07	2.83	2.14
2000	3.77	3.11	2.45	1.86
2001	3.41	2.81	2.26	1.71
2002	3.74	3.05	2.56	1.95
2003	4.53	3.75	3.08	2.35
2004	5.29	4.41	3.51	2.63
2005	5.74	5.21	3.61	2.81
2006	6.10	5.53	3.70	2.89
2007	6.73	6.03	4.04	3.18

Norway

Year	Premium Gasoline (95 RON)	Diesel Fuel	Gasoline Tax	Diesel Fuel Tax
1999	4.48	4.04	3.35	2.70
2000	4.55	4.26	3.12	2.72
2001	4.03	3.64	2.73	2.12
2002	4.25	3.89	2.97	2.30
2003	5.01	4.49	3.45	2.65
2004	5.61	4.88	3.74	2.85
2005	6.35	5.78	4.10	3.18
2006	6.76	6.04	4.24	3.27
2007	7.55	6.69	4.72	3.64

Spain

Year	Premium Gasoline (95 RON)	Diesel Fuel	Gasoline Tax	Diesel Fuel Tax
1999	2.82	2.28	1.89	1.40
2000	2.86	2.43	1.69	1.28
2001	2.61	2.24	1.56	1.18
2002	2.90	2.46	1.81	1.39
2003	3.49	2.97	2.18	1.67
2004	4.09	3.55	2.43	1.87
2005	4.49	4.20	2.48	1.96
2006	4.84	4.50	2.55	2.02
2007	5.37	4.97	2.79	2.25

Switzerland

Year	Premium Gasoline (95 RON)	Diesel Fuel	Gasoline Tax	Diesel Fuel Tax
1999	3.01	3.11	2.08	2.16
2000	3.14	3.22	1.89	1.95
2001	3.03	3.14	1.88	1.94
2002	3.15	3.25	2.02	2.09
2003	3.69	3.82	2.34	2.42
2004	4.27	4.40	2.55	2.64
2005	4.64	4.98	2.56	2.67
2006	4.96	5.26	2.57	2.68
2007	5.31	5.58	2.69	2.83

United Kingdom

Year	Premium Gasoline (95 RON)	Diesel Fuel	Gasoline Tax	Diesel Fuel Tax
1999	4.29	4.45	3.50	3.60
2000	4.58	4.66	3.45	3.46
2001	4.13	4.25	3.15	3.16
2002	4.15	4.28	3.22	3.23
2003	4.70	4.82	3.55	3.57
2004	5.56	5.68	4.09	4.11
2005	5.97	6.25	4.13	4.17
2006	6.36	6.64	4.24	4.28
2007	7.14	7.34	4.76	4.79

Source: International Energy Agency, *Energy Prices and Taxes* (Second Quarter 2008), available by subscription or purchase from web site www.oecdbookshop.org/oecd/.