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HEALTH EFFECTS INSTITUTE

The Future of Vehicle Fuels and Technologies: Anticipating Health Benefits and Challenges

HEI Special Committee on Emerging Technologies

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Health Effects Institute

Boston, Massachusetts

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NOTE TO READERS:
Each chapter in this report describes specific technologies or fuels, the likelihood of their use, their emissions, life-cycle issues, and regulatory issues. Chapter 6 provides a concise summary and the Committee's conclusions.

ABOUT HEI

The Health Effects Institute is a nonprofit corporation chartered in 1980 as an independent research organization to provide high-quality, impartial, and relevant science on the effects of air pollution on health. To accomplish its mission, the institute

- Identifies the highest-priority areas for health effects research;
- Competitively funds and oversees research projects;
- Provides intensive independent review of HEI-supported studies and related research;
- Integrates HEI's research results with those of other institutions into broader evaluations; and
- Communicates the results of HEI's research and analyses to public and private decision makers.

HEI receives half of its core funds from the U.S. Environmental Protection Agency and half from the worldwide motor vehicle industry. Frequently, other public and private organizations in the United States and around the world also support major projects or certain research programs. This project, in particular, was partially supported by the Federal Highway Administration.

HEI has funded more than 280 research projects in North America, Europe, Asia, and Latin America, the results of which have informed decisions regarding carbon monoxide, air toxics, nitrogen oxides, diesel exhaust, ozone, particulate matter, and other pollutants. These results have appeared in the peer-reviewed literature and in more than 200 comprehensive reports published by HEI.

HEI's independent Board of Directors consists of leaders in science and policy who are committed to fostering the public–private partnership that is central to the organization. The Health Research Committee solicits input from HEI sponsors and other stakeholders and works with scientific staff to develop a Five-Year Strategic Plan, select research projects for funding, and oversee their conduct. The Health Review Committee, which has no role in selecting or overseeing studies, works with staff to evaluate and interpret the results of funded studies and related research.

All project results and accompanying comments by the Health Review Committee are widely disseminated through HEI's Web site (*www.healtheffects.org*), printed reports, newsletters and other publications, annual conferences, and presentations to legislative bodies and public agencies.

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COMMUNICATION 16

The Future of Vehicle Fuels and Technologies: Anticipating Health Benefits and Challenges

HEI Special Committee on Emerging Technologies

CHAPTER 1. INTRODUCTION

Driven by a need for energy independence, increased fuel efficiency, and concerns about climate change and reduction of air pollutant emissions, the development of new fuels and technologies for the transportation sector is moving forward at an unprecedented pace in the United States and other parts of the world. The mission of the Health Effects Institute (HEI*) is to understand the health consequences of exposure to emissions from vehicles and other sources in the environment. Therefore, HEI decided to assess the nature and pace of new fuels and technologies, along with potential unintended consequences of their use. To do this effectively, HEI established in 2009 a Special Committee on Emerging Technologies (SCET) composed of leading experts in a range of disciplines relevant to assessing new fuels and technologies.

SCET produced *The Future of Vehicle Fuels and Technologies: Anticipating Health Benefits and Challenges* to provide HEI with a compilation of those automotive technologies and fuels that are likely to be commercially available within the next 10 years in the United States at a level of market share that could result in population exposure. The report highlights expected changes in emissions and other effects from the use of each technology and fuel examined. The primary audience for the report is HEI's Research Committee, which will review the projections and trends in the use of these technologies and fuels and identify the potential health implications that may arise from these developments. This assessment of fuels, technology, emissions, and potential effects on health is designed to be a key resource in guiding HEI's decisions to determine the priority areas for future research to inform regulatory and other decisions during the next 10 years.

In general, the Committee has avoided quantifying the impact on fuel efficiency of the technologies and fuels included in this report or to delineate their benefits in terms of greenhouse gases (GHGs). The rationale for this choice is that technologies and fuels may be used on different vehicle platforms by different manufacturers, with or without other processes, to reduce fuel consumption and improve efficiency, and the engines may be tested under different conditions. The Committee has mostly relied on qualitative statements. The purpose of this report, thus, is to elucidate, as well as possible, how each technology may affect emissions, environmental quality, GHG emissions, and, in turn, what effect it may have on health in a qualitative fashion.

Although the main scope of this report is the study of emerging technologies and fuels in the United States, and to some extent, Europe and Japan, the Committee has also addressed technologies and fuels in the developing countries wherever appropriate.

CONTEXT

The technology of motor vehicles, and especially that of the powertrains, continues to improve and change (Heywood and Welling 2009). Tailpipe emissions have been drastically reduced in response to stringent emission regulations; however, there continues to be a compelling need for attainment of regulatory standards in many parts of the United States (U.S. Environmental Protection Agency [EPA] 2010a), which frequently include reductions in vehicles' emissions. After a hiatus of about 20 years, average fuel consumption of vehicles sold in the United States has begun to improve, and new regulations limiting carbon dioxide (CO_2) emissions and increasing fuel economy requirements — along with concerns about supplies and cost of petroleum — will accelerate this trend (U.S. EPA and National Highway Traffic Safety Administration 2010). These regulatory requirements, along with the rising cost of fuel and concerns about supplies, will provide pressure to increase the extent and pace of changes in technology and fuels.

Work of the HEI Special Committee on Emerging Technologies was supported with funding from the United States Environmental Protection Agency (Assistance Award CR–83234701) and motor vehicle manufacturers. Support for the preparation and publication of this Communication was provided by the Federal Highway Administration (Grant DTFH61-09-G-00010). This report has not been subjected to peer or administrative review by any of the sponsors and may not necessarily reflect their views, and no official endorsement should be inferred.

* A list of abbreviations and other terms appears at the end of this report.

The discussion in this report has implicitly assumed that, broadly speaking, new technologies are suitable for new fuels and vice versa. However, the problem of matching engines and fuels with each other is receiving much attention. Questions are being raised, such as: How far should the engines be optimized for the use of a specific fuel? And, how far should a fuel's composition be optimized for use with a specific engine technology? In other words, greater attention to the fuel–engine *system* should be paid. Though important, consideration of such issues was beyond the scope of this report.

TECHNOLOGIES

Emission controls in gasoline engines and associated catalyst technologies for the reduction of hydrocarbons, carbon monoxide (CO), and oxides of nitrogen (NO_x) are highly effective and continue to improve. Technologies for the reduction of particulate matter (PM) emissions from diesel engines are maturing rapidly. Technologies for reducing NO_x from diesel engines are becoming available and are being continuously improved.

A variety of factors govern the output of emissions from a vehicle, including the powertrain and emissions control technologies, the engine's average operating efficiency, the vehicle's weight, size, and relative performance capability (for example, acceleration and speed), along with the fuel used as the source of power, and driver behavior and driving conditions. Vehicle-based technologies and fuels also strongly affect the vehicle's fuel (or energy) consumption and hence its GHGs. They also have a concomitant impact on emissions of criteria and toxic air pollutants.

In this report, the Committee examines the more promising options for future powertrains in on-road vehicles (which dominate transportation's contribution to urban air pollution and significantly affect global GHG emissions). As much as possible, the Committee has provided a brief description of the technologies, commented on their likelihood of use and the time frame, assessed their emissions and other potential impacts, and discussed any specific regulatory issues. The powertrain developments considered include mainstream gasoline and diesel engines and the anticipated changes in their component technologies, as well as hybrids, plug-in electric hybrid vehicles (PHEVs), battery-powered electric vehicles (BEVs) and fuel-cell vehicles (FCVs).

The Committee also evaluated anticipated changes in exhaust-aftertreatment technologies — that is, particle filters and catalysts. These assessments are intended to provide guidance as to the relative attractiveness of the different powertrain and aftertreatment technologies and the impact they are likely to have on fuel consumption and GHG emissions, as well as on toxic and unregulated pollutants. Where appropriate, the Committee has also made comments on the relative costs of technologies, although this discussion is cost qualitative, like those of most of the other factors considered in the report (for more quantitative estimates, see National Research Council [NRC] 2010). In assessing future powertrain and aftertreatment developments, the Committee has used today's mainstream gasoline and diesel engine technologies as baselines.

This report describes the technologies that hold the most promise for significantly improving the efficiency of these baseline gasoline and diesel engines as well as the more promising alternatives to the internal combustion engine technologies that are close to or already in limited production. The prospects for these new technologies and any related emission concerns — chiefly how they might contribute to air pollution problems — are the primary focus.

Because of the special nature of electric-drive vehicles, which use special technologies allowing them to use electricity as the source of power, electric vehicles (EVs) are discussed in a separate chapter that bridges considerations related to technologies and fuels.

FUELS

After considering the existing and upcoming technologies, the Committee focused on fuels. This report provides HEI with a "roadmap" of fuel use and related issues that are projected for the next 10 years. Significant changes in the mix of transportation fuels in the marketplace are anticipated; the factors driving such changes include:

- The need to reduce GHGs
- The rate of introduction of new automotive technology
- The need for improvements in ambient air quality
- The need for reduced reliance on imported petroleum and petroleum products
- The rate of utilization of resources from agricultural and forestry sectors
- The availability of new sources such as natural gas from shale
- The price of petroleum and petroleum products

Use of ethanol is increasing, mostly blended with gasoline; there is also some use as E85 (85% ethanol with 15% gasoline) in flexible-fuel vehicles. Other fuels that could be produced from biomass are being explored. BEVs and PHEVs are entering the market. If production volumes of such vehicles grow to become a significant part of total sales, then the use of electricity as a major fuel in transportation will become important. The use of natural gas as a source of energy is on the increase, mostly for power generation, chemical production, and home heating. It is used on a fairly limited basis in the United States for transportation, and although the prospects for expanded use in the United States are not clear, the use of natural gas in transportation in Europe and Asia is increasing. The use of hydrogen as a fuel for transportation may well emerge in the next 5 to 10 years. The supply of gasoline and diesel from oil sands and heavy oils (crude oil with high viscosity and high hydrogen-to-carbon ratio) is steadily increasing, but because of the higher energy demands that extraction and production require, the associated GHG emissions are likely to be higher, too, than those from fuels derived from petroleum. The environmental impact of extraction is also a cause for concern.

As noted above, the Committee took a broad view and included nontraditional fuels such as electricity in the report. We recognize that indirect factors may affect fuel choices. Such indirect factors include changes in emissions that may result from the use of different sources to produce fuel. For instance, heavy crude may generate more emissions than conventional crude oil in the processing steps, but this source will produce fuel that is equivalent to conventional fuels. Recognizing the challenges inherent in understanding this complex area, the Committee also looked at fuels from the perspective of life-cycle analysis and GHG emissions for a broader determination of the impact of fuel choices on these issues. Finally, indirect impact on land use from widespread use of biofuels continues to be an area of intense interest and uncertainty; whereas the Committee recognized these issues, it was beyond the scope of this report to perform a detailed evaluation.

Throughout this analysis, the Committee relied largely on detailed assessments done by others, and used such published data as well as its own judgment to reach a conclusion as to the expected evolution of these promising technologies and fuels.

CHAPTER 2. NEW TECHNOLOGIES

The need to improve fuel economy and the need to reduce both GHG emissions and other pollutants are driving major changes in the automotive sector, and this trend will continue during the next decades. State and federal governments as well as international organizations have mandated improvements along these lines. The internal combustion engine will continue to improve and remain the dominant technology for the next two or so decades, although we are likely to see an increase in powertrain electrification and the use of nonpetroleum fuels within this period.

How much room is left to improve the efficiency of conventional internal combustion engines? It appears likely that — at a constant vehicle weight and performance — continuous improvements in the conventional internal combustion engine can lead to a reduction of 30% to 50% in fuel consumption of light-duty vehicles (LDVs) over the next 20 to 30 years (Bandivadekar et al. 2008; NRC 2010). Such improvements will come from steady advances in weight reductions (made possible by the use of new materials and innovative designs), better aerodynamics, electronic controls, and other changes (such as variable valve timing, transmissions with more gears, and cylinder deactivation). The use of biofuels, powertrain electrification, and hydrogen-fuel cells will lead to improvements in the average fuel consumption across the fleet, as well. Improvements in traffic management and other social policies could yield added benefits.

The extent to which the various technologies and fuels will penetrate the market in the future — and thus the ultimate benefit they will provide — will depend on a variety of factors, including technology cost, fuel cost, availability of required infrastructure, government policy, customer preferences, and more. The Committee attempted to qualitatively assess the likelihood of use of each option, recognizing there are uncertainties in any future projection. Also, the Committee focused mostly on technologies that are likely to have an effect on emission characteristics. Extensive discussions of all the technologies, their costs, and their impacts have recently been published (NRC 2010; U.S. EPA 2008).

ENGINE MODIFICATIONS

Gasoline Direct-Injection Engines

The dominant technology used to control the fuel flow in gasoline engines has been port injection; however, the direct injection of fuel into the cylinders of gasoline engines is increasingly being used because it improves fuel efficiency and performance. Although the gasoline direct-injection (GDI) system is more expensive than the port-injection system, it provides better control of the air-to-fuel ratio, especially while starting an engine and during warm-up. Another important feature of the GDI is that it allows the use of a higher engine compression ratio, made possible because of cooling of the in-cylinder air charge as the direct-injected fuel spray evaporates. Because of the less complete mixing of fuel vapor and air, however, the particulate emissions of the engine increase, including the number of ultrafine particles (UFPs; particles that are less than 100 nm in diameter). The timing of fuel injection is important, therefore, because earlier fuel injection provides better mixing and lower PM emissions. Direct-fuel injection also enables effective turbocharging and engine downsizing (discussed below). Two different approaches have been developed to use the direct-fuel injection concept: stoichiometric (homogeneous) and lean burn (stratified).

Gasoline Direct Injection — Stoichiometric (Homogeneous)

Description of the Technology In a GDI-stoichiometric engine, fuel is injected at high pressure directly into the combustion chamber instead of upstream of the intake valve. Direct injection provides better fuel vaporization, more flexibility as to when the fuel is injected, and a more stable combustion event. The heat of vaporization of the fuel lowers the charge temperature, which reduces engine knock and allows for higher compression ratio and higher intake pressures with reduced levels of enrichment. GDI is particularly effective in improving fuel efficiency when combined with turbocharging and engine downsizing. The stoichiometric combustion also allows efficient use of the well-developed three-way catalyst to treat emissions; this is an advantage in comparison to lean-burn direct injection, which requires more complex aftertreatment to reduce PM and NO_x emissions.

Likelihood of Use and Time Frame Because of the difficulties presented by lean-burn combustion (discussed below), automotive companies are preferentially adopting the use of GDI-stoichiometric. Such engines — in combination with turbocharging and engine downsizing — are currently in use in automotive applications around the globe, with most major manufacturers offering them. In view of the increasing pressure for improvements in fuel efficiency and reduction in CO_2 emissions, the use of GDI-stoichiometric technology is likely to become widespread during the coming decade.

Emissions of Potential Concern The major concern arising from the use of GDI-stoichiometric engines is higher emissions of PM, both total mass and UFPs, although such emissions are less than those from lean-burn engines. UFPs emitted from GDI-stoichiometric engines have not been well characterized, though research in this area is currently underway.

Life-Cycle Issues None.

Specific Regulatory Issues The regulatory issues raised by the use of GDI-stoichiometric engines are the increased mass of PM (which can be reduced by refinements in fuel injection that minimize contact with the combustion chamber walls and valves) and the production of UFPs. Control of emissions of NO_x is not a concern because of the stoichiometric mixture and use of a three-way catalyst.

Currently, there are no standards for UFPs, although this is an area of potential health concern. Perhaps the most far-reaching expression of concern regarding UFPs is in Europe, where a standard based on the number of particles will be phased in for all diesel vehicles starting in 2011 and will be fully in place by 2013. This standard is being implemented less because of specific health questions and more to ensure that diesel-exhaust particle filters (DPFs) are installed on all diesel vehicles. A particle number standard will also be extended to all gasoline engines, starting in 2014 and with full implementation by 2015 (DieselNet 2010). For gasoline-powered, lean-burn GDI vehicles to meet such a standard, auto manufacturers may need to employ a particulate trap, as discussed below. The California Air Resources Board, in the context of proposed rules to implement its Low-Emission Vehicle (specifically LEV III) regulations for light-duty and medium-duty vehicles, is currently considering an optional particle number standard that would be based on Europe's Particulate Measurement Programme (PMP) and would include solid particles down to 23 nm in size (California Air Resources Board 2010a). The PMP measurement method accounts for only solid particles; in contrast, the particle mass standards include both solid *and* volatile particles. There is an ongoing debate about what the lower size cutoff should be and whether volatile particles should be counted.

Gasoline Direct Injection — Lean-Burn (Stratified)

Description of the Technology Lean-burn (stratified-charge) GDI allows operation with excess air in the cylinder chamber, reducing the amount of intake throttling, thus reducing pumping losses and fuel consumption. In the lean-burn mode, fuel is injected near the spark plug during the compression stroke to create a stratified charge near the spark plug (U.S. EPA 2008). Under certain operating conditions, the air-to-fuel ratio can be as high as 20:1 to 40:1 (as compared with 14.7:1 for stoichiometric combustion). The advantages of lean-burn GDI technology are reduced pumping losses and reduced heat losses (the excess air reduces combustion temperature, which in turn reduces heat loss to the cooling and exhaust systems). Lean-burn combustion, when combined with engine downsizing and turbocharging, can result in useful improvement in fuel economy above what GDI-stoichiometric technology can achieve.

Likelihood of Use and Time Frame Lean-burn GDI engines began to appear in the mid-1990s, primarily in Japan and Europe, and continue to be used today on a limited basis. In areas with stringent NO_x emission requirements, aftertreatment costs are higher than for stoichiometric engines, and PM controls may be necessary in the future. Use of gasoline with very low sulfur is also required due to the adverse effect of sulfur on lean-exhaust aftertreatment systems. These considerations are likely to limit the widespread use of this technology, and currently no manufacturer in the United States has plans to introduce this technology. To the extent that sulfur limits in gasoline fuel are reduced, or more sulfur-tolerant lean NO_x catalytic converters are developed, use of this technology could expand in the future. However, because of the higher PM emissions from such engines, a particle trap may also be required.

Emissions of Potential Concern With the lean-burn GDI engine, as with the GDI-stoichiometric engine, PM mass and particulate numbers increase as compared with conventional gasoline engines. Due to excess air in the combustion chamber, the exhaust from lean-burn GDI engines is lean, an environment in which the conventional three-way catalyst does not work well; therefore, emission control requires the use of a lean-NO_x catalytic converter or similar technology (Tashiro et al. 2001), adding to the overall cost. Also, because the fuel is added later during the combustion cycle, there is less time for mixing of fuel and air, increasing the emissions of PM above those from a GDI-stoichiometric engine.

Life-Cycle Issues None.

Specific Regulatory Issues As mentioned above, compared with emissions from GDI-stoichiometric engines, lean-burn GDI engines can produce higher NO_x emissions, which must be controlled by the use of a lean-NO_x catalytic converter. Such catalytic converters can be poisoned by sulfur in the exhaust. Therefore, gasoline with very low sulfur levels, at or below 10 to 15 parts per million (ppm), is needed to achieve low NO_x control. Gasoline sulfur limits vary throughout the world; in the United States, the currently allowed levels are 30 ppm (average) and 80 ppm (maximum). Reductions in the sulfur level of fuel would greatly facilitate deployment of lean-burn GDI engines. Issues related to control of PM from GDI engines are discussed above in the section about GDI-stoichiometric engines and apply to lean-burn GDI engines as well.

Turbocharging and Downsizing Gasoline Engines

Description of the Technology In a turbocharged engine, the turbocharger compressor increases the density of the air entering the engine cylinders. Exhaust gases flowing through the turbocharger turbine drive this compressor. Thus, more fuel can be burned in a given size engine, increasing its torque and power. The engine can then be downsized (and the maximum speed reduced).

The abnormal phenomenon of knock in gasoline-engine combustion limits both the compression ratio of the engine and the extent to which it can be boosted or turbocharged. GDI technology reduces the impact of these constraints on turbocharged engine operation. The injection of fuel directly into the cylinder cools the in-cylinder air charge as the gasoline spray evaporates when the fuel drops move through this air. This evaporative cooling effect offsets the onset of knock (which is caused by excessively high temperatures of the unburned mixture during combustion) and allows higher boost. As a result, the low compression ratio of traditional turbocharged engine designs can be substantially increased. Thus, as discussed above, turbochargers are being widely used, along with GDI and engine downsizing, to enhance fuel efficiency of gasoline-powered vehicles.

Likelihood of Use and Time Frame The use of turbochargers for gasoline engines — in combination with engine downsizing — is increasing rapidly to increase fuel efficiency, especially with GDI technology. Turbochargers have been used on gasoline engines around the world for many years. Recent refinements in turbochargers, including variable geometry, improved materials, and other factors, have increased the reliability and performance of these units over those of just a decade ago (U.S. EPA 2008). In the future, it is likely that most turbocharged gasoline engines will use direct-fuel injection.

Emissions of Potential Concern The engine-out pollutant emissions levels in turbocharged engines may be somewhat higher than for a standard gasoline engine, and the thermal loading on the exhaust catalyst system can be higher. These problems can be resolved, although there are some concerns regarding cold starting with turbocharging, under the proposed LEV III standards in California. Still, no critical concerns related to emissions and the use of turbocharging are expected.

Life-Cycle Issues None.

Specific Regulatory Issues None.

High-Efficiency Dilute Gasoline Engine

Description of the Technology In view of the increasingly tighter emission standards for diesel engines, some of its efficiency and cost advantages are being compromised. Therefore, there has been interest in exploring ways to use gasoline engine technologies for heavy-duty applications (Alger et al. 2005), but more recently, attention has shifted to applications in the light- and medium-duty market. In high-efficiency dilute gasoline engine (HEDGE) technology, exhaust gas recirculation (EGR) is used to reduce throttling losses and to mitigate engine knock. EGR is used to control the amount of air inducted into the combustion chambers and a stoichiometric mixture is created. The EGR extends the knock margin, which allows more advanced timing and improved fuel economy. Finally, by using a base engine with high peak cylinder pressure capability, the engine can be downsized and down-speeded — which also reduces fuel consumption. Furthermore, as with lean-burn GDI, the dilute operation achieved with EGR reduces combustion temperature and heat losses. HEDGE technology integrates mostly existing technologies that allow a gasoline-fueled engine to operate at torque-per-liter and thermal-efficiency levels comparable to modern diesel engines, but at a substantially lower engine and aftertreatment cost. Development of cost-effective ignition systems, component durability, exhaust-catalyst technology, and sensor technology is the present focus of research in this area.

Likelihood of Use and Time Frame Modern gasoline engine development continues at a rapid pace, especially with the introduction of GDI engine technology in the last 5 years. There is also a trend toward using highly diluted lean-burn GDI engines. Given the current pace of gasoline technology advancement and the potential benefits of HEDGE, there is interest in this technology for the light- and medium-duty markets, as noted. Early versions of “HEDGE-light” can be found in the third-generation Toyota Prius, currently on the market. The use of HEDGE technology is likely to expand during the next few years.

Emissions of Potential Concern Conventional HEDGE technology is presumed to operate under stoichiometric conditions using the conventional, durable three-way catalyst that is used almost universally with gasoline engines. Therefore, regulated emissions are expected to meet recent California Air Research Board LEV III standards or better. Particulate and other nonregulated emissions are not expected to be significantly different from those of gasoline engines available today. Two studies (Mohr et al. 2003; Alger et al. 2010) suggest that particle number emissions may be an issue relative to more stringent standards under discussion in the European Union (EU). Thus, particulate filtration may be necessary for future gasoline engines, whether they employ a HEDGE approach or more conventional gasoline architecture. There are also some remaining concerns regarding cold-start emissions and combustion stability (emissions). The emissions profile from highly diluted, stoichiometric engines, however, is expected to be different in that such engines are not likely to produce very much NO_x and PM, although they may produce increased levels of hydrocarbons and aldehydes.

Life-Cycle Issues None.

Specific Regulatory Issues See above under Emissions of Potential Concern.

Homogeneous Charge Compression Ignition

Description of the Technology Homogeneous charge compression ignition (HCCI) is an engine combustion process that has potential for improving the efficiency of internal combustion engines while reducing pollutants in the exhaust. HCCI may be considered a special case of low temperature combustion, which is discussed below. A very lean fuel–vapor air mixture, usually hotter than in standard gasoline engines, is compressed in the engine cylinders to a sufficiently high temperature to cause spontaneous ignition. Alternatively, a dilute fuel, air, and residual gas plus EGR mixture can be used. The combustion of these extremely lean or dilute mixtures in an internal combustion engine produces low NO_x emissions with the potential for higher efficiency. The fuel and air mixture has to be well mixed in HCCI engines for efficient, controlled autoignition. Also, the compression-ignited combustion process starts at multiple points, which is inherently difficult to control (while compression ignition is also used in a conventional diesel engine, the timing of the ignition is controlled by injecting fuel into already compressed and hot air, leading to a rapid initiation of combustion; with HCCI, air and fuel are premixed).

Another challenge has to be overcome as well: achieving spontaneous (or compression) ignition requires higher temperatures at the end of compression, which can lead to a main combustion event that occurs too fast. The high pressure and temperature can result in engine damage or accelerated wear because they exceed the engine’s mechanical capacity. With HCCI and its more recent rendition — partially premixed compression ignition — the air and fuel are usually partially premixed (and stratified); this helps to control both the ignition event and the burn rate. There is also a problem of deposits in the combustion chamber of HCCI engines. Further, this novel combustion process cannot yet be employed at high or very low engine power levels, so it needs to be combined with standard spark-ignited engine operation at these higher and lower engine load conditions, thus reducing some of its benefits. Some of the difficulties noted above with the HCCI approach are related to the chemical composition and combustion properties of current fuels; it is possible that the most appropriate fuel for HCCI engines will be different from today’s gasoline and diesel fuels, possibly raising emissions and regulatory issues.

Likelihood of Use and Time Frame HCCI is currently in the development stage with continuing research, prototype engines, and a limited number of concept vehicles. The applications of HCCI have been explored for both gasoline and diesel engines, although the interest is greater for diesel (see section on low-temperature diesel combustion below). The current prognosis of this engine technology is that unless the problems and tradeoffs outlined above are resolved, improvements in mainstream spark-ignition engine efficiency and emissions control will render the benefits marginal.

Emissions of Potential Concern NO_x emissions with HCCI combustion are substantially lower than in standard gasoline engines. Still, the spontaneous ignition of very lean or dilute mixtures is not as complete as the traditional spark-ignited flame propagation combustion process, so the emissions of hydrocarbons, aldehydes and CO are higher. It is anticipated that catalysts in the exhaust system will be needed to meet the levels being set for future regulations for emissions levels. With lean-engine operation, and low exhaust gas temperatures, the effectiveness of the NO_x catalyst is significantly lower than that of current three-way catalyst performance with stoichiometric mixtures. While PM emissions from homogeneous HCCI engines are not likely to be a concern, it is not known whether PM emissions may be produced from stratified versions.

Life-Cycle Issues None.

Specific Regulatory Issues None.

Low Temperature Diesel Combustion

Description of the Technology The problem of emissions of NO_x and PM in diesel engines arises from the engine's diffusion-flame combustion process. High fuel–air mixture temperatures at the end of compression are required to achieve rapid, spontaneous ignition. These high-compression temperatures result in high burned-gas temperatures within the stoichiometric diffusion flame that forms around each individual diesel fuel spray, resulting in high rates of nitric oxide (NO) formation. The very rich mixture within each diesel fuel spray is at high temperature and pressure, which results in high rates of soot formation. If combustion in the diesel engine could occur at lower temperatures and with better mixed fuel–air mixtures (less rich or even leaner than stoichiometric mixtures), then both the rates of NO_x and soot formation would be significantly lower. This approach is called low-temperature diesel combustion.

To date, a full realization of low-temperature combustion in a practical diesel engine has not been achieved. With multiple fuel injections in each engine cycle — which is now feasible with piezoelectric fuel injectors and common rail fuel injection systems — and EGR, the standard diesel combustion process is shifting in this direction. An early injection, or even preinjection, of a small fraction of the total fuel is being used to prime the combustion of the main fuel injection pulse so that the main combustion process occurs faster, is thus more robust, and can be started later (after the piston has reached its top center position). Thus, parts of the overall combustion occur under lower temperature conditions and with a better mixed fuel. Such approaches are continuing to be examined and developed, and are starting to be used in production engines.

Likelihood of Use and Time Frame It seems unlikely that fully implemented low-temperature diesel combustion technology will be commercialized within the next decade. In the shorter term, partial use of low-temperature diesel combustion will provide, at the very least, an opportunity for modest reduction of the cost of the total engine combustion system.

Emissions of Potential Concern The lower chamber temperature reduces exhaust temperature and catalyst efficiency, resulting in higher hydrocarbon, aldehyde and CO emissions; PM emissions are generally quite low. In the short term, low-temperature diesel combustion will be used only in a narrow engine operating window, where DPFs and NO_x-reduction systems are likely to be used; the impact on levels of vehicle emissions is likely to be modest under such conditions. However, there are concerns about cold starts and, when the low-temperature diesel combustion is used over a wider operating range, further characterization of emissions will be necessary.

Life-Cycle Issues None.

Specific Regulatory Issues None.

EXHAUST AFTERTREATMENT

Technology for the control of emissions from conventional port-fuel injection gasoline engines is mature and has been stable for some time. In combination with clean fuels (low sulfur and no lead additive), and with exhaust-oxygen sensors, catalyst efficiencies of 99.7% for hydrocarbons and 99.5% for NO_x are being achieved using the three-way catalyst converters; such vehicles can meet the very stringent super ultra-low emission vehicle standards, as proposed by the California Air Resources Board. As discussed above, some of the emerging engine technologies highlight the need for development of improved catalysts; active research is underway to develop such catalysts.

The picture for emissions control from diesel-powered vehicles has evolved rapidly during the last decade. The major problem in the past has been emissions of high levels of soot. Soot emissions have been largely addressed by the use of efficient particulate traps and ultra low-sulfur diesel fuel. The catalysts used on some traps, however, increase the levels of nitrogen dioxide (NO_2) markedly, although total NO_x remains essentially the same. Reduction of NO_x emissions has lagged behind control of diesel soot and several strategies are now being used to control NO_x, most notably the selective catalytic reduction (SCR) systems that are beginning to be introduced in the heavy-duty diesel market in the United States, starting in 2010. The U.S. EPA requires that the DPF-SCR systems be durable for 435,000 miles or 10 years or 22,000 hours, with severe penalties for noncompliance. As a result, emissions from diesel engines now entering the U.S. market are substantially lower than those from older diesel engines.

Diesel Particle Filters

There are many types of DPFs but, in the United States, the so-called wall-flow filter is by far the most common filter for transportation applications. It consists of a honeycomb-like ceramic structure with alternate passages blocked (Fino 2007; Johnson 2008). Wall-flow filters are extremely effective at removing diesel PM, with removal efficiencies typically well over 95%. There are a variety of other types of filter media; these include ceramic foams, sintered metal, and those made of wound, knit, or braided fibers. All of these filters have qualitatively similar emission performances and differ mainly in durability, cost, and packaging. Disposable, low-temperature fibrous paper filters that can only be used with cooled exhaust have been used in niche applications such as underground mining and are not considered here.

High-efficiency particle filters can quickly become loaded with soot particles, which must be removed to prevent plugging. Removal is done by oxidizing the collected soot particles in place in a process called regeneration. Temperatures of 600°C or more must be reached to oxidize soot in engine exhaust, but such high temperatures are never reached in normal engine operation. Therefore, other means must be used to achieve regeneration. There are two types of regeneration processes, passive — where soot is oxidized at lower temperatures with the aid of an oxidation catalyst — and active — where heat is added to reach exhaust temperatures sufficient for soot combustion; within each category a number of designs are available.

DPFs Using Passive Regeneration

Description of the Technology Passive DPFs are used mainly in retrofit applications; essentially all DPFs installed in new trucks use some form of *active* regeneration. However, passive regeneration plays an extremely important role even in active systems because it is associated with little or no fuel-consumption penalty. Several types of catalysts are used in passive DPFs to reduce the soot-oxidation temperature. The Johnson Matthey trap — from a leading manufacturer — or, as it is known, the continuously regenerating trap (CRT) (Allansson et al. 2002), positions a NO_2-generating, precious metal-oxidizing catalyst, generally platinum, upstream of the uncatalyzed DPF; this catalyst converts NO in the exhaust to NO_2. NO_2 is a strong oxidizing agent that reacts rapidly with soot at temperatures between about 250° and 450°C. In applications where the exhaust temperature is above 250°C a significant fraction of the time, e.g., in over-the-road trucks, the CRT does exactly what its name implies. A variant, called the catalytic continuously regenerating trap (CCRT), has a catalytic coating; a rare earth metal such as platinum is added to the DPF itself, which facilitates regeneration and helps overcome problems with the lower temperature limit. Another version of a passive system is exemplified by the Engelhard DPX; Engelhard is another major manufacturer of filters. This is a catalyzed DPF, which also converts NO to NO_2 to oxidize the soot, but in this case the NO_2 formation takes place within the filter itself rather than in an upstream catalyst; an advantage of this system is that it needs smaller amounts of the precious metal catalyst. Because of concerns about NO_2 emissions, new low-NO_2 versions of CRTs — such as the advanced CCRT — are now available that meet the California 2009 requirements for unreacted NO_2 emissions (the so-called NO_2 slip) (Johnson Matthey Emission Control Technologies 2009).

Another way to achieve passive regeneration is to use a fuel-borne catalyst. In this case a metallic catalyst, typically some combination of cerium, strontium, and iron is added to the fuel. During the combustion process, catalytic metallic nanoparticles become intimately mixed with the soot, making it much more reactive so that oxidation can take place at temperatures below 400°C (Vincent et al. 1999; Vincent and Richards 2000). This technology has been around for about 10 years and has seen some level of use in retrofit applications outside of the United States. However, there are concerns about metallic emissions resulting from introduction of metals into fuels, and fuel-borne catalysts are not being pursued in the United States.

Likelihood of Use and Time Frame Use of various versions of the continuously regenerating traps and catalytic DPFs has increased in heavy-duty retrofit applications over the past 10 years. As we will discuss, an active version of a catalyzed CRT or DPF is the most widely used system for heavy-duty diesel truck engines built in the United States since the 2007 model year. Passive regeneration DPFs are generally not suitable for use in light-duty diesel applications because the exhaust temperature in light-duty diesel vehicles is often lower than 250°C (however, all light-duty diesel vehicles sold in the United States since 2004 have active DPFs and meet or exceed the EPA Tier 2 standards).

Emissions of Potential Concern The emissions of concern from the DPFs that use NO_2 to oxidize the soot are NO_2 and nanoparticles. The amount of NO_2 formed in these devices is considerably more than what is consumed during soot oxidation and the excess NO_2 is emitted from the tailpipe (Gense et al. 2006). If DPFs are used in a stand-alone system without additional de-NO_x devices, then the emissions of NO_2 may raise environmental and health concerns. The catalysts that convert NO to NO_2 are also effective at converting SO_2 from fuel and lube oil combustion to sulfuric acid, which then nucleates to form nanoparticles as the exhaust dilutes in the atmosphere (Vaaraslahti et al. 2004; Grose et al. 2006). These systems also store sulfates and release them when exhaust temperature is high (Swanson et al. 2009). Such release could lead to emission "hot spots" under certain traffic conditions. Sulfur in the fuel also degrades catalyst performance. Therefore, the use of these systems was limited before ultra-low sulfur diesel fuel became widely available. Fuel consumption penalties from increased back pressure are small, typically 1% to 2% or less.

Metallic fuel additives that serve as fuel-borne catalysts are used in some European vehicles and for some aftermarket applications (Richards et al. 2006). The main emissions of concern are metallic nanoparticles that could be released in the event of a filter failure. It is difficult to obtain approval from the EPA (U.S. EPA 2009) or the California Air Resources Board to use metallic fuel additives; however, other countries remain interested in uses of fuel-borne catalysts. The use of metallic fuel additives appears to cause only very small fuel consumption penalties. (See further discussion in the section on fuels.)

DPFs Using Active Regeneration

Description of the Technology All new diesel-powered passenger cars sold in Western countries use some form of active regeneration (Twigg and Phillips 2009). Since Peugeot introduced the first widely used active DPF system in 2000, several million diesel passenger cars using this technology have been sold. The system combines a silicon carbide wall-flow filter with an upstream oxidizing catalyst, active fuel-injection control, and a cerium-based fuel-borne catalyst (Salvat et al. 2000). Exhaust temperatures associated with passenger car operation are usually too low to allow passive regeneration so the pressure drop across the filter is monitored; whenever it becomes excessive, additional fuel is injected into the cylinder late in the cycle. This fuel is oxidized over the catalyst, raising the exhaust temperature sufficiently high to start regeneration.

The Johnson Matthey company recently introduced a compact soot filter, an active DPF for European passenger cars (Twigg 2009). In this device, the oxidizing catalyst and DPF are integrated and the device is mounted very close to the turbocharger outlet. The combination of close coupling to raise the operating temperature of the device and zoned catalyst design eliminates the need for a fuel-borne catalyst and decreases the fuel consumed during regeneration. The device may lead to some NO_2 and sulfuric acid nanoparticle emissions, but emissions from such systems have not been well characterized.

In the United States, the main application for DPFs is in trucks and buses because the light-duty diesel vehicle market is very small. Nearly all the vehicles sold in the United States since the 2007 model year use an active version of a catalyzed DPF system. These devices combine passive regeneration with active regeneration whenever the pressure drop across the DPF (or some other measure of filter loading) indicates excessive soot buildup. These systems also include a diesel oxidation catalyst (DOC), which is positioned upstream of the DPF. The DOC converts NO in the exhaust to NO_2, which plays a role in active regeneration. Active regeneration is accomplished by injecting fuels into the exhaust stream; the combustion of fuel raises the DOC temperature, leading to combustion of the accumulated PM and soot.

Likelihood of Use and Time Frame Since the 2007 model year, all new diesel engines sold in the United States, both heavy duty and light duty, are equipped with an active DPF. In Europe, active DPF for LDVs started to be used in 1999 and are widely used today.

Emissions of Potential Concern The Advanced Collaborative Emissions Study (ACES) has been organized by the Health Effects Institute. ACES has recently completed a detailed study characterizing the emissions under a variety of driving cycles from four 2007-compliant heavy-duty diesels (HDDs) equipped with a DOC and DPF (different designs of devices were used by different manufacturers). The levels of criteria pollutants as well as about 300 unregulated air pollutants in the emissions were measured in the study (Coordinating Research Council 2009). The investigators reported that emissions of PM, carbon monoxide, and nonmethane hydrocarbons were at least 90% below the EPA 2007 standard; average NO_x emissions were 10% below the standard. The engines were fitted with either a DOC and a catalyzed DPF or only with a DPF with a means of active regeneration. The real-time particle-number concentrations (diameter 5.6 to 30 nm) during regeneration were several orders of magnitude higher than the particle-number concentrations without active regeneration; however, the authors point out, the average particle-number emissions were about 90% lower than those emitted with the use of 2004 technology. For the next phase of the study, currently underway, ACES has launched an animal bioassay to study the health effects of inhalation exposure to emissions from one of the four engines tested earlier; the results will be available in 2013.

Even though the levels of pollutants are substantially reduced, the issue of the toxicologic potential of the remaining compounds remains an area of interest. For example, in a recent study, engines fitted with a variety of DPFs were tested for the oxidative potential of PM in the exhaust (Biswas et al. 2009); oxidative potential is widely considered to be an indicator of the potential to cause biological injury. The DPF reduced the oxidative potential by 60% to 98% when expressed per vehicle distance traveled; when expressed per unit mass, there were substantial differences among the various devices. In the aforementioned ACES study, total nitro-polycyclic aromatic hydrocarbon (nitro-PAH) emissions from the 2007 engines were lowered by 81% when compared with 2004 engines, but nitro-PAH emissions for the 16-hour cycle were not zero and were a factor of two to three times higher than background levels. Nitrosamines were also detected in the emissions.

As indicated above, passive regeneration plays an important role in the operation of active systems, so that the so-called active systems share many characteristics of passive systems. Thus NO_2 and sulfate nanoparticles remain potential emissions of concern. The ACES program showed that nanoparticle emissions during the 16-hour test cycle were undetectable except during regeneration. Thus, the potential for exposure to nanoparticles is greatest under operating conditions that lead to regeneration. The U.S. emission standards for 2010 heavy-duty trucks strongly reduce NO_x emissions, so even though NO_2 may constitute half or more of NO_x emissions, the absolute levels are low.

For DPFs that are used in combination with fuel-borne catalysts that typically contain some combination of cerium, strontium, and iron compounds, there is also a concern regarding emissions of metallic ash in case of a failed filter.

DPFs are quite effective in reducing the emissions of PM — as well as a variety of other compounds, except NO_2 — from diesel engines. However, some of the observations discussed above also underscore the importance of ongoing research and vigilance in monitoring emissions from DPF devices. In Europe, DPFs used in LDVs have been very stable and durable. Although the certification standards for the performance of DPFs for heavy-duty applications are quite stringent in the United States, little information is currently available on the durability and stability of these filters in actual use. The fuel-consumption penalty associated with these systems depends upon the driving cycle, with little or no penalty for highway driving where regeneration is mainly passive. Low-temperature start-stop operations lead to frequent regeneration and fuel consumption penalties of up to several percent.

Aftermarket and Retrofit Systems

Description of the Technology DPFs with passive regeneration like the CRT, CCRT, and catalytic DPF described above are widely used around the world in retrofit applications. The applications must be chosen carefully to ensure that the operating cycle provides exhaust temperatures above 250°C a significant fraction of the time. Generally light-load and start-stop applications are inappropriate. Other types of DPF retrofit systems use off-line regeneration. With these systems the DPF is heated, generally electrically but sometimes with a burner, to cause regeneration. Regeneration may occur with the device in place or with it removed and installed in a separate heating appliance. There are other types of retrofit systems that use active, on-line regeneration systems with burners and sensors.

A DOC consists of a flow-through structure similar to that used on gasoline engine three-way catalysts, with a platinum or platinum-palladium catalyst. Its main advantages are simplicity and low cost. DOCs oxidize NO, CO, and hydrocarbons, but they do not oxidize PM because the temperature of the exhaust is not high enough. Before DPFs became available, DOCs were widely used as the primary emission-control system on diesel passenger cars and light trucks (California Code of Regulations 2007; Toussimis et al. 2000). DOCs are still a common retrofit technology for heavy-duty trucks and buses (U.S. EPA 1999; California Air Resources Board 2000) and are used extensively in underground mines.

A variant on the DOC is the so-called partial-flow or open filter (Heikkilä et al. 2009; Mayer et al. 2009). This type of device combines elements of DOCs and DPFs by either using convoluted flow passages to direct a portion of the flow over the filtration medium or simply by having a filtration medium that has a very open structure. These filters are usually catalyzed to allow passive regeneration. Reports on the effectiveness of these devices are mixed, ranging from little or no PM mass removal efficiency (Mayer et al. 2009) to nearly 80% (Heikkilä et al. 2009). The remaining PM is emitted and is an environmental and health concern. Interest in these devices stems mainly because they are less likely than DOCs to become plugged and they reduce the levels of hydrocarbons by oxidation. Some modern engines may have low enough engine-out PM emissions to meet current standards with little or no aftertreatment; in such cases, partial-flow devices may be considered. The problem with such devices is that, like a DOC, they do not qualitatively change the nature of PM emissions, so that emissions of concern would be similar to that of a DOC except at slightly lower levels. These systems are also reported to be subject to particle blowoff under some operating conditions. At present, the devices have limited use for transportation applications, although there is interest in their use for off-road applications to meet Tier 4 emission standards.

Likelihood of Use and Time Frame Aftermarket retrofit filter systems are being deployed on a fairly wide scale, spurred by special programs and mandates from state and federal governments in the United States and Europe. Retrofit applications are available for many heavy-duty vehicles (HDVs) built during 1994 to pre-2007.

Emissions of Potential Concern DPF and DOCs used in retrofit applications have similar emissions to those described above though the precise composition depends on the catalyst(s) used; however, the emissions from retrofit devices have been even less well characterized. Because DPF systems do not reduce NO_x emissions, most diesel engine manufacturers plan to use additional technologies to control NO_x emissions. NO_2 emissions, currently not directly regulated, are a concern for catalyzed DPF systems, unless measures are taken to control NO_2, as in the advanced CCRT. Storage and release of sulfates might also be a problem under some conditions; for example, under high-load conditions, sulfate-based nucleation mode nanoparticles can form in the aftertreatment system. It should be noted that these nanoparticles will not be measureable under the EU's PMP particle-number measurement protocol. Finally, some retrofit DPFs contain vanadium pentoxide, which is unstable at high temperatures and its vapors are a cause for concern (see below).

DOCs, used for retrofit and other applications, have a more limited impact on emissions. They lead to an increase in nitrogen dioxide emissions (Liu and Woo 2006; Majewski 2009). Further, DOCs do not remove solid carbon or ash particles, though organic compounds adsorbed to the PM are combusted. In addition, unless low-sulfur fuel is used, sulfate or sulfuric acid particles and nanoparticles are also emissions of concern (Maricq et al. 2002). The DOC device is effective for removing CO, hydrocarbons, and organic carbon (a part of the PM) from emissions. In addition, because DOCs do not remove organic carbon particles when cold, various schemes have been developed to store hydrocarbons during engine warm-up. There is no significant fuel-consumption penalty.

Life-Cycle Issues None.

Specific Regulatory Issues Both California and the U.S. EPA now require retrofit filters to demonstrate that NO_2 emissions are less than 20% of NO_x emissions.

Selective Catalytic Reduction and Ammonia Slip Catalyst

Description of the Technology Because diesel engines operate under lean conditions, reduction of NO_x to nitrogen gas is particularly challenging. Originally developed for stationary sources, selective catalytic reduction (SCR) technology is designed to reduce NO_x emissions. A reductant, typically ammonia (NH_3) or urea, is injected into the exhaust stream for the chemical conversion (Majewski 2005a,b). Urea serves as an alternative source of NH_3 because it thermally decomposes to NH_3.

For most on-highway motor vehicle applications, zeolite catalysts, using urea as the reductant, are the system of choice. Zeolites are microporous crystalline aluminosilicate minerals, found naturally or produced artificially, and are often referred to as "molecular sieves." By substituting other metals for the aluminum and silicon, these structures can be adapted for a wide variety of catalytic purposes. For motor vehicles, most manufactures have settled on the use of iron- and copper-exchanged zeolites or a combination of the two. A more detailed description of SCR technology can be found in Majewski (Majewski 2005a,b). Future developments in SCR technology may use cerium, titanium, or tungsten to promote acidic zirconia SCR catalysts (Rohart 2008).

If NH_3 is not fully consumed in the catalytic process, it is emitted in the exhaust, a process referred to as ammonia slip. An ammonia slip catalyst is commonly used to control such emissions. It is an oxidation catalyst, typically with a platinum-based formulation (Majewski 2005b). This catalyst can lead to the formation of nitrous oxide (N_2O), a GHG as well as an ozone-depleting gas (Havenith and Verbeek 1997; Ravishankara et al. 2009; Wuebbles 2009).

In view of the need to reduce CO_2 emissions, another trend in this area should be noted: to improve efficiency, heavy-duty diesel engines are being calibrated to lower PM levels and higher engine-out NO_x levels. Therefore, higher efficiency de-NO_x technologies will be required in the future, increasing efficiency percentages from the low 90s in 2010 to the high 90s, later in the decade. To achieve such high efficiency, more urea will have to be injected into the SCR, which could lower the exhaust temperature. Given the wide operating range of diesel engines, it is conceivable that secondary emissions of urea-related by-products will increase. Therefore, this area deserves continuing attention.

Several alternatives to the use of urea are also being investigated. One of these alternatives relies on the reduction of NO_x by hydrocarbons (Parvulescu et al. 1998; Liu and Woo 2006). The catalyst used to accomplish this is similar to urea-SCR except that fuel or reformed fuel (a hydrogen and CO mixture) is used as a reducing agent instead of urea. So far, hydrocarbon-SCR has not proved successful for a number of reasons: the temperature window corresponding to high conversion efficiency is limited; the fuel consumption penalty is large; and NO_x emissions (Twigg 2007) are a concern. The combination of increased fuel consumption and the emissions of NO_x — a potent GHG — raises questions about the impact of this technology on climate change. However the technology may be improving as Tenneco and GE Transportation have recently announced plans to jointly develop hydrocarbon-SCR technology for diesel locomotives and some nonroad applications (Green Car Congress 2009). Additionally, the use of solid metal amine chloride salts used as an NH_3 storage system for the replacement of aqueous urea is also being considered, since such compounds have a high specific NH_3 storage capacity (Fulks et al. 2009).

Likelihood of Use and Time Frame A federal NO_x standard of 0.20 g/bhp-hr (grams per brake horsepower-hour) has been phased in for diesel engines between model years 2007 and 2010. For the 2010 model year, most major HDD manufacturers (e.g., Cummins, Detroit Diesel, Mack, Paccar, and Volvo) are using the urea-SCR system, thus the use of SCR is expected to increase rapidly in the United States. However, one manufacturer (Navistar) plans to use an EGR- or NH_3-SCR system to meet the standard (Dixon 2009). SCR is currently being used in Europe and Japan for HDD applications, and more than half a million diesel trucks in Europe now use urea SCR and the numbers are rapidly increasing (Green Car Congress 2008). Further tightening of CO_2 regulations will drive engine-efficiency improvements further, resulting in higher NO_x emissions and the need for more effective SCR systems. However, because such efforts will also lead to lower exhaust temperatures, the task of developing better SCR systems will be challenging.

For LDVs, urea-SCR systems are already in use in Europe and the United States (e.g., in Mercedes-Benz, BMW, and Audi vehicles). The market penetration for these diesel systems in the light-duty fleet may reach levels of 5% to 15% in the United States (Tim Johnson, Director, Emerging Technologies and Regulations, Corning Incorporated, 2009, personal communication). In Europe, the light-duty diesel fleet is expected to decrease, chiefly because of the shrinking differential between the price of gasoline and diesel fuels. Oxidation catalysts are currently being deployed in Europe and Japan, and very likely to be used in the United States, to control NH_3 slip from SCR systems. A high market penetration for this technology is expected.

Emissions of Potential Concern The introduction of urea into the exhaust system represents a large departure from conventional emission-control systems; our understanding of the chemical reactions within the catalyst and resulting emission products is quite poor at this time. Studies with the urea-SCR system have indicated the presence of nitrogen-containing compounds, including nitro-PAHs. For example, various studies have indicated the presence of nitrosamines (Farber and Harris 1984), nitromethane, nitropropane, hydrogen cyanide, and increases in NO_x (Sluder et al. 2005), and melamine (Hori and Oguchi 2004). Although more systematic studies are needed before reaching any final conclusions, it should be noted that nitrogen-containing organic compounds are often toxic or biologically active, making the presence of these compounds in the emissions an area of potential health concern. However, there is also a concern that some of the detected chemicals may be the result of artifacts of sample collection. There is an additional issue in that the exhaust from SCR systems may contain novel nitro-organic compounds and possibly others for which appropriate sampling and analytical methods are not available; thus, there is a need to develop analytic methods to detect and characterize such compounds. A comprehensive study on emissions from 2010-compliant HDD engines is planned as a part of ACES. These engines will be equipped with DPF and devices designed to remove NO_x, and the study will characterize a large number of regulated and unregulated compounds in the exhaust.

A recent study in Europe raised questions about the effectiveness of SCR for reducing NO_x emissions (Ligternik et al. 2009). Seven trucks that met the Euro V emissions standard were driven according to standardized procedures. Emissions of NO_x were about three times higher than previously estimated for urban driving. Problems with urea injection during stop-and-go driving, where exhaust temperatures are generally lower, have been reported (Xu et al. 2007; Zhan et al. 2010). At higher speeds, NO_x emissions were greatly reduced. However, this study's report did not provide information about composition of the SCR catalyst employed in the trucks. Furthermore, it should be noted that there are significant differences between the emissions standards and compliance requirements in the United States and those in Europe, with those in the United States being more stringent; these differences make it problematic to extend the Euro V data to the United States.

There has been concern related to the use of copper-based zeolite catalysts used in some SCR systems. Copper is an extremely potent catalyst for dioxin formation, and there is the possibility that SCR with copper may lead to dioxin emissions (Heeb et al. 2007). A study performed by EPA investigators was presented at a recent Society of

Automotive Engineers (SAE) meeting. Based on the testing to date of a 2007 heavy-duty diesel Cummins engine equipped with a retrofitted and mildly aged copper/zeolite SCR catalyst only (without urea injection), no statistically significant differences were seen between the engine-out dioxin/furan emissions and the SCR-out dioxin/furan emissions. Additional testing has yet to be conducted on the comparison of a complete catalyst system (i.e., a copper/zeolite SCR catalyst compared to an iron/zeolite SCR catalyst, with both including an oxidation catalyst, urea injection, particulate filter, and NH_3 slip catalyst) (Laroo 2010). Copper-iron-zeolite catalysts are desirable because they have the best performance in reducing NO_x over a broad temperature range (Majewski 2005b).

Some early SCR catalyst formulations included vanadium pentoxide deposited on titanium dioxide, with tungsten trioxide often added as a cocatalyst or promoter. However, one study reported vaporization of vanadium pentoxide when heated to above 580°C; emission of vanadium pentoxide is of health concern. However, as noted above, most automotive SCR systems rely on zeolite-based formulations, although some vanadium-based systems may be used for retrofit applications and off-road applications. Vanadium catalysts are cheaper and more sulfur-tolerant than the copper-iron-zeolite variants, but vanadium-based systems are not stable at higher temperatures (Johnson 2010).

Finally, there is also a concern that truck drivers may continue driving after urea in the on-board storage tank has been depleted. This issue remains controversial and is likely to be addressed using engine cut-off switches and regulatory enforcement actions.

In summary, based on available information, it is anticipated that the combination of DPF and urea-SCR systems will substantially reduce criteria pollutants in emissions from diesel engines. Although emissions of toxic, unregulated species are expected to be low or very low, conclusions regarding their overall risk are difficult to draw at this point because such exhaust has not been characterized systematically or in detail. Although the performance standards for diesel aftertreatment devices are very stringent in the United States, little information is available at this time concerning the long-term performance and stability of DPF-SCR devices. All these issues deserve further study.

Life-Cycle Issues There are no known significant life-cycle issues related to the deployment of urea-SCR technology. Urea is used for many purposes in the chemical industry. Some large-scale urea spillages have occurred, resulting in wildlife deaths. Accidental localized spills associated with SCR-related urea distribution and infrastructure may occur, but are not expected to pose any significant health or environmental concerns.

Specific Regulatory Issues As mentioned above, SCR emission-control technology has been developed to meet the federal 2010 emission requirements for NO_x (0.20 g/bhp-hr), which apply to virtually all on-road heavy-duty diesel engines (e.g., line-haul trucks, buses, refuse trucks). DPF-SCR devices are also being used on most new light-duty diesel vehicles. European heavy-duty diesel emission standards (Euro VI) will become effective between 2013 and 2014, and approach the 2010 U.S. emission standards; the European standards will, however, remain less stringent.

Given that limited data exist on NH_3 emissions from production-ready heavy-duty diesel vehicles equipped with SCR, further study of this issue is warranted. At present, there are no federal limits on NH_3 emissions for new vehicles or retrofit applications. The California Air Resources Board has not yet set an NH_3 standard for new vehicles, but has put a limit on NH_3 emissions from retrofit applications, mandating that “the diesel emission control strategy must not increase the emissions of NH_3 to a level greater than 25 ppm by volume at the tailpipe on average over any test cycle used to support the emission reduction claims” (California Code of Regulations 2007). It appears likely that the EU will cap NH_3 emissions to 10 ppm in the Euro VI regulations for heavy-duty diesel vehicles.

NO_x Adsorber Catalyst Technology

Description of the Technology The NO_x adsorber catalyst (NAC) is also commonly referred to as the lean-NO_x trap, the NO_x storage-reduction catalyst, and the NO_x storage catalyst. It is predominantly used in diesel engines and is a multifunctional, cyclically operated catalyst unit, with two major operation phases: trapping and regeneration. During the trapping phase, the NAC removes NO_x from the exhaust by oxidizing and storing it on the catalyst, in the form of a nitrate. This process occurs under excess oxygen (lean) conditions typical for diesel exhaust. During the rich regeneration phase, for a few seconds every minute, NO_x, is released from the catalyst and chemically reduced to nitrogen by excess reductant, typically by injecting diesel fuel. The key catalytic functions inherent to a NO_x adsorber are oxidation, trapping, reductant transformation, and reduction. To satisfy these requirements, a NAC must contain a capable reduction-oxidation component such as platinum and rhodium (as in a three-way catalyst) and a storage component with basic properties, such as alkali or alkaline-earth metal compounds. The storage component also traps sulfur oxide (SO_x) species originating from fuel and lubricating oil, leading to a progressive decrease in the NO_x-trapping capacity. The NAC is best used with very low-sulfur fuel. Removal of SO_x is accomplished under high-temperature, rich conditions (Epling et al. 2004), which can also damage the catalyst. NAC technology is used as a part of a system that includes both a NAC and other catalytic components, typically oxidation catalysts and catalyzed diesel particulate filters (Majewski 2007; Yezerets et al. 2007).

Likelihood of Use and Time Frame NAC technology is often used for LDVs and has been used commercially in several diesel-powered vehicles, for example Toyota Aventis, Dodge Ram pickup, Mercedes E320, and Volkswagen Jetta. Further market penetration of this technology is likely in smaller light-duty diesels, and lean-burn GDI applications (Majewski 2007).

Emissions of Potential Concern During the NO_x regeneration phase, NAC can produce N_2O and NH_3 as byproducts of NO_x reduction (Pihl et al. 2006). However, now that there is a better understanding of the regenerative process, the levels of these emissions have been minimized. For example, as determined independently by several research groups, the produced NH_3 is rapidly consumed inside the catalyst, acting as a NO_x-regeneration agent (Cumaranatunge et al. 2007; Clayton et al. 2008; Lietti et al. 2008; Lindholm et al. 2008). As an example, the Dodge Ram NAC system produces no measurable emissions of NH_3. Another strategy involves manipulation of the regeneration conditions to intentionally create NH_3 slip from a NAC (Parks et al. 2008). This slip is created in the systems where NH_3 is consumed by a downstream SCR catalyst, as in the Mercedes E320 system (Majewski 2007). In both cases, NH_3 emissions out of the NAC system are negligible.

During SO_x regeneration, NAC can produce hydrogen sulfide as a byproduct of SO_x reduction. Another reduced sulfur product, carbonyl sulfide, has been observed, but

IMPACT OF VEHICLE TECHNOLOGIES ON CLIMATE

The most likely routes through which new technologies may affect climate change are by gains (or losses) in fuel efficiency, emissions of non-CO_2 GHGs, and emissions of soot. Regarding fuel efficiency, the Committee has refrained from stating specific numerical values for gains or losses in fuel efficiency in this report because such effects are intimately linked to many other factors, such as overall engine configuration and testing conditions, to name just two. Also, such changes in efficiency are evolving constantly as manufacturers find ways to make gains in engine and automobile design.

Gains in fuel efficiency will lead to a decrease in CO_2 emissions from the tailpipe and thus will have a net beneficial effect on the climate. Each gallon of fuel saved reduces CO_2 emissions by approximately 8.8 kg. The gains in efficiencies from technologies such as GDI (especially when deployed with turbocharging and engine downsizing) and hybrid electric vehicles (HEVs) are fairly clear and well accepted. The fuel efficiency penalty from the use of DPF and SCR is likely to cause a rather modest effect in increasing CO_2 emissions; however, the reduction in black carbon emissions associated with aftertreatment technologies may well compensate for the increased CO_2 emissions. In other cases, however, the reduction in tail-pipe CO_2 emissions may be offset at least partially by displaced emissions at other sites — for example at power plants, in the case of EVs. If the major source of power in the United States continues to be coal, the gains in efficiency from EVs may well be canceled by power plant emissions, resulting in no overall decrease in GHG emissions. However, as the carbon intensity of the electricity delivered to the vehicles is reduced with the use of renewable sources, for instance, the climate benefits of EVs and similar technologies will be enhanced. The development of cost-effective carbon capture and storage (CCS) technologies may also enhance these benefits, although this technology is not expected to be commercially available during the time frame considered by this Committee.

There is a broad trend in automotive engineering to improve fuel efficiency for gasoline engines — and decrease CO_2 emissions — with greater use of EGR and other processes that lower the combustion or exhaust temperatures. The impact of such changes on emissions deserves attention. For example, lower combustion temperatures could also lead to higher engine-out hydrocarbon emissions as well as a longer heat-up period and perhaps a lower catalyst performance, especially during cold starts. There is potentially a similar concern regarding HEVs, which shut off the engine during idling (see chapter 3, Electric Drive Technologies).

Some technologies appear to produce small amounts of other GHGs, such as N_2O, that affect the climate. By and large, such gases are found in relatively small amounts in automobile emissions and are not likely to have a major impact on climate.

Finally, the contribution of black carbon or soot to climate change is being widely appreciated now, and though estimates vary, it is likely to be a significant contributor to climate change on the global scale. Technologies, such as DPF, that greatly reduce the emissions of PM, therefore, would be expected to exert a net positive effect in terms of climate change.

only under laboratory conditions in the absence of water vapor. Carbonyl sulfide reacts rapidly with water vapor to form hydrogen sulfide and CO_2. Strategies for hydrogen sulfide emission mitigation are well known and broadly commercially applied in the three-way catalyst industry sector. Similar measures are implemented in the NAC systems. As a result, sulfur is emitted from the NAC systems in the same form as from engines that were not aftertreated, namely as SO_x. Thus, the, NAC system does not lead to substantial increases in N_2O, NH_3, or hydrogen sulfide emissions, as compared with a non-aftertreated engine.

Life-Cycle Issues None.

Specific Regulatory Issues None.

CHAPTER 3. ELECTRIC DRIVE TECHNOLOGIES

Electric drive technologies — HEVs, PHEVs, BEVs, and FCVs — have started to be marketed in many countries during the last few years. HEVs have high fuel efficiency and good performance, and their perceived environmental benefits attract consumers. Pollutant emissions are comparable to the cleanest available gasoline engines. HEVs were first introduced in the market approximately 10 years ago; they now account for a few percent of new LDV sales (J.D. Power 2010). PHEVs, which can be recharged by plugging into a traditional 110V or 220V outlet (depending on the design), can be recharged at home, allowing partial “refueling” with electricity. Their larger battery increases their sales price. In the U.S. market, the first commercial PHEV, the Chevy Volt, arrived in late 2010. The Telsa roadster, a full-performance BEV was first introduced in 2008 but its high cost — primarily because of the battery — has limited its sales to less than 2000 vehicles. The Nissan Leaf, a 100-mile range but otherwise full-performance compact sedan BEV, also went on sale in late 2010. Honda introduced its fuel-cell Clarity in a limited commercial demonstration in 2008. Most automobile manufacturers are prepared to market FCVs and some have announced plans for their availability in just a few years, but point to the need for hydrogen infrastructure before large-scale commercialization can become a reality.

HYBRID ELECTRIC VEHICLES

Description of the Technology HEVs combine a combustion engine, electric drive, and a battery. A wide variety of designs is being used that aim to combine the engine, electric motor, generator, mechanical drive, and energy storage. The simplest employ a belt drive motor-generator to stop the engine while idling without providing any electrical tractive force. There are three general classes of full HEVs, which allow significant electrical assist in powering the vehicle and regeneration during braking: parallel (combined electric and mechanical drive); series (only electric drive); and mixed series and parallel (power split, with features of both parallel and series).

The HEV reduces fuel consumption by a combination of factors, including idle-stop (shutting down the gasoline engine when the vehicle stops or coasts); regenerative braking; engine down-sizing; facilitating electrification of accessories; and allowing the engine to operate at higher efficiency for a greater fraction of the time. Reduction in fuel consumption can be as high as 50%, depending on the sophistication of the design and how the vehicle is operated. Improvements in power electronics, motor generators, and batteries enhance the performance and reduce the cost of HEVs. Most HEVs use nickel-metal hydride batteries, but the introduction of lithium-ion batteries in the U.S. market began with the 2010 Mercedes S400 Hybrid and the use of these is likely to spread. The Toyota Prius, the current leader in the hybrid class of vehicles in the United States, employs additional fuel-saving methods, such as improved aerodynamics, EGR, the Atkinson-cycle engine, and low-rolling resistance tires.

Likelihood of Use and Time Frame Commercial production of HEVs began in 1998 in the United States. In 2008, 3.1% of cars and 0.9% of trucks sold in the United States were HEVs (U.S. EPA and National Highway Traffic Safety Administration 2010); this category of vehicle is the largest segment of the electrified vehicles. The combination of technology improvements and more stringent fuel economy and GHG regulation will assure an increasing fraction of HEVs in the light-duty fleet. Penetration of HEVs in the future is difficult to predict. A study from the Massachusetts Institute of Technology depicted a “no clear winner” scenario in which 22.5% of new car sales will be HEVs and PHEVs in 2035 (Bandivadekar et al. 2008). Greater uncertainty is associated with the possibility of a transformative technology, such as BEVs or FCVs supplanting HEVs (Kromer and Heywood 2007).

Emissions of Potential Concern Although the unique operational characteristics of HEVs may require different strategies for calibration and compliance with emissions standards than conventional internal combustion engines, HEVs are not expected to introduce any new or unique emissions of concern. In fact, many hybrids on the market today in the United States are among the lowest-emitting vehicles available. Some diesel-fueled HEVs are beginning to be introduced, especially in the European market.

There appears to be little information available on any increased exposure to electromagnetic radiation of drivers and passengers in HEVs; although such exposures may be limited, they may pose a public health concern as HEVs (and other automobiles with batteries and motors) become more common. This area deserves attention.

Life-Cycle Issues Life-cycle issues specific to HEVs relate to the production, use, and disposal of batteries — as well as to the constituent metals of the batteries, such as nickel and lithium. Given the high value of such metals, it is very likely that they will be largely recycled. However, lithium is highly reactive chemically, and the potential harm for humans from exposure during metal mining and refining, and during battery manufacturing, disposal and recycling, as well as from accidental exposures (such as from car crashes) has not been fully evaluated. The batteries also contain highly flammable electrolytes, which are of potential concern in accidents. Special training of emergency workers — to avoid contact with battery contents and high voltage — will be necessary. Although there are plentiful supplies of lithium on the global market, there are concerns about the supply of rare earth elements that are needed to make certain components of EVs, for example neodymium for electric motors (Service 2010; Jacoby and Jiang 2010). Note that these concerns are also applicable to all electric drive-train vehicles that have batteries.

Specific Regulatory Issues None.

PLUG-IN HYBRID ELECTRIC VEHICLES

Description of the Technology The possibility of fueling vehicles with electricity is enabled by providing increased battery capacity to an HEV. Still, because of the limited power storage available with existing batteries, PHEVs have a gasoline engine to extend the overall driving range. Thus, PHEVs allow displacing some hydrocarbon fuel with electricity. This technology is currently in the early commercialization phase. There are designs that employ larger batteries, which are sufficient to provide 10 to 40 miles all-electric range, and charging from the electric power grid.

Likelihood of Use and Time Frame The Chevrolet Volt (about 40 miles all-electric range and referred to as a range-extended EV) has recently become available in the United States. The high cost of the larger battery and uncertainty related to actual cost savings from displacing gasoline by electricity may affect market acceptance. Other designs, such as the PHEV version of the Toyota Prius, have smaller batteries and shorter all-electric range.

Emissions of Potential Concern Tailpipe emissions should be comparable to those of the HEV and combustion-engine vehicles, which must be certified to the same emission standards. However, the upstream source of the electricity will have emissions associated with electrical power generation. Important pollutants from traditional coal-fired power plants — which provide about half of the electricity used in the United States — include particulates, SO_2, NO_x, mercury, and CO_2; these emissions can be greater than those associated with the displaced hydrocarbon fuel. Because there is considerable geographic variability in the power-plant sites, such increased emissions may accentuate regional differences in air pollution within the United States. Issues arising from the potential for electromagnetic field exposures are discussed in the HEV section.

Life-Cycle Issue Life-cycle issues associated with the manufacture of batteries and recycling are discussed in the HEV section, and may be more difficult to resolve because of the increased battery size. However, because of the need for greater storage space for batteries, PHEVs are likely to use lithium batteries, rather than the nickel metal hydride used in most of today's HEVs.

Specific Regulatory Issues No regulatory issues have been identified. However, there are questions related to the impact of increased electricity demand for battery charging on the power grid — for example, the potential use of these batteries to smooth grid load as well as off-peak power pricing — that may receive regulatory attention.

BATTERY ELECTRIC VEHICLES

Description of the Technology Historically, BEVs were among the first automotive designs. Because of the high battery cost and low energy density compared to hydrocarbon fuels, combustion engines became and remain the dominant vehicle-propulsion device. Today's BEVs range from small, limited-speed, limited-range cars to full-performance passenger cars, but the total number remains low.

Likelihood of Use and Time Frame Improvements in permanent motors, power electronics, and batteries, resulting largely from HEV applications, are helping enable two current applications: compact, limited-range vehicles and high-performance vehicles. Simplified powertrain design (compared to combustion engine, transmission, and emissions controls) and improved low-speed performance are advantageous characteristics. High battery cost and low energy density (compared to liquid hydrocarbon fuels), along with limited driving range and the time needed for recharging, remain the major disadvantages of many BEVs. In addition, problems with operability of BEVs (and PHEVs) in high- and low-temperature conditions, due to battery performance, may also pose a challenge, although auto and battery manufacturers appear to be making progress in solving these problems.

High-performance, full-range BEVs (for example, the Tesla) have entered the market, but carry a very high price, in excess of $100,000. Several original equipment manufacturers have prototype BEVs in demonstration testing in Japan, China, Europe, and the United States. Nissan began to ship its Leaf BEV in the United States at the end of 2010. Nissan is building a battery factory and EV assembly plant in Tennessee with an eventual capacity of 150,000 vehicles and 200,000 vehicle batteries. The Leaf has a range of 75 to 100 miles. The recharging options including 120 V (slow), 240 V (overnight), and 400 V DC (20–30 minutes). A battery-swapping scheme is being promoted by a company called Better Place, but such ideas appear to be at very preliminary stages. In the near future, BEVs are most likely to be adopted as compact vehicles that operate within a limited range.

Emissions of Potential Concern As discussed above, emissions associated with power generation may be a cause for concern, depending upon the process used for power generation. Emissions from electromagnetic fields and their potential health effects remain uncharacterized and unassessed for all EVs.

Life-Cycle Issues Concerns related to batteries and metals are discussed in previous sections.

Specific Regulatory Issues Overall regulatory issues for BEVs are similar to those for HEVs and PHEVs, but compliance with emissions standards is greatly simplified for the manufacturers because there are no tailpipe emissions from a BEV.

FUEL-CELL VEHICLES

Description of the Technology Current FCVs are hybrids wherein the fuel cell replaces the internal combustion engine. The battery allows the FCV to meet transient vehicle-power demand. Improved vehicle efficiency provided by an HEV configuration allows reduction of fuel-cell stack size and hydrogen gas storage size and mass. This technology has progressed rapidly with substantial support from both government and industry. Several manufacturers have small fleets of prototype-production vehicles in the hands of businesses and private individuals. Demonstration fuel-cell transit-bus fleets exist in the United States and Europe, and several manufacturers have announced plans to begin to market FCVs during the few next years. FCVs have drawn great interest among auto manufacturers because they can provide full performance over a range of vehicle sizes and also meet zero tailpipe and zero GHG emissions goals (depending on the source of hydrogen). All manufacturers appear to be using high-pressure hydrogen storage. On-board reforming of a hydrocarbon fuel is another possibility, but this is not being currently pursued.

Hydrogen can also be burned in an internal combustion engine. This technology has been demonstrated by BMW. Tailpipe emissions are very low except for NO_x, which can be controlled. Because of the lower efficiency of internal combustion engines compared to fuel cells, greater quantities of hydrogen must be carried on board. BMW has addressed this by using liquefied hydrogen, which introduced the need for a liquefied hydrogen-fueling network. Because of fuel-supply issues associated with hydrogen internal combustion engines, and the apparent lack of interest on the part of manufacturers as compared to interest in FCVs, introduction of this technology seems unlikely within the time frame we are considering.

Likelihood of Use and Time Frame The major barriers to introduction of FCVs are the cost and lack of fueling infrastructure. As in the case of BEVs and PHEVs, the source of electricity and contribution of associated GHG emissions should be considered in evaluating the overall benefits of electric-drive vehicles. Electrolysis and natural gas reforming are existing technologies that are seeing early introduction. Natural gas reforming at petroleum refineries could provide a large central source of hydrogen, with distribution in high-pressure tanks or by pipeline. Germany plans to create a countrywide fuel network of 1000 hydrogen stations by 2015.

Emissions of Potential Concern Without an onboard reformer, FCVs are a zero tailpipe-emissions technology. The primary emissions are those associated with the production, compression, and delivery of the hydrogen. On-board electromagnetic field issues are common with HEVs, PHEVs, and BEVs.

Life-Cycle Issues Battery production and recycling issues are common with the other electric-drive vehicles. As with electricity, the upstream source of hydrogen can have significant emissions, involving a range of air pollutants and GHG emissions. New processes for the thermochemical production of hydrogen may bring new emissions issues.

Specific Regulatory Issues Regulatory issues primarily concern safety associated with high-pressure hydrogen and the wide flammability limits of hydrogen. As with other high-voltage applications, special training of emergency personnel is required.

QUESTIONS RELATED TO FUELS FOR ELECTRIC DRIVE TECHNOLOGIES

Electricity and hydrogen are the two new fuels for electric-drive vehicles. Liquid fuels — discussed in other parts of the report — are used in HEVs and can be used in PHEVs to drive them part of the time. It is expected that the liquid fuels used in these vehicles will be the same as those used in standard internal combustion engines. Although hydrogen could be used in internal combustion engines vehicles, more efficient use may lie in FCVs. Therefore, the discussion of fuels for electric-drive vehicles includes electricity and hydrogen only.

Electricity as a Fuel

The environmental impact of the use of electricity as an automotive fuel has two major distinguishing features: the nature of emissions during electricity generation and the geographic location of these emissions. As we move through the technology spectrum from internal combustion engine powered by fossil fuels through HEVs to PHEVs to BEVs, the source of air pollution emissions moves from the vehicle tailpipe to the power sector that generates the electricity to drive the vehicle. Although there are substantial regional and temporal variations within the United States, the national average electricity generation mix is roughly 50% from coal, 20% from nuclear power, 18% from natural gas, 1% from oil, and less than 1% from biomass; the remaining 10% is derived largely from hydropower, with geothermal, wind, and solar sources contributing small amounts. Other countries have different mixes of fuel for power generation. China depends on coal for 80% of its electricity; Brazil has significant amounts of hydropower; and France generates large amounts of power using nuclear energy.

Overall, coal is the predominant source of energy for producing electricity worldwide. Its combustion produces emissions of SO_x, NO_x, PM, and mercury as well as CO_2. Technologies to dramatically reduce all but CO_2 exist but add to the cost of electricity production. Most planning for increased use of EVs for transportation assumes that the conventional pollutants and climate-related emissions will have to be substantially reduced through emission controls, alternative energy sources, and possibly CCS.

There are a number of potential alternatives, although few that do not raise questions. Biomass-fired power plants generate a number of particulate and gaseous pollutants, but their CO_2 emissions are in part renewable because of the carbon used by plants during biomass growth. There continue to be concerns related to nuclear waste disposal and accidental release of radiation from nuclear power plants. Hydropower plants, especially large ones, may cause ecological damage. Geothermal power plants may create concerns about water pollution and air emissions. Solar and wind power produce no carbon emissions, although siting of such facilities has become controversial, especially for wind farms in some parts of the country.

Thus, although vehicles with electric powertrains may not produce emissions on roadways where they are used, electricity generation at distant sites and the accompanying emissions of GHGs and other pollutants should be taken into consideration when evaluating their overall environmental impact. Even though power plants are generally not located in densely populated areas where tailpipe emissions have their greatest impact, in the absence of effective pollution control, the short- and long-range transport of the pollutants is a major source of concern for human health and the environment. Such transport raises additional challenges when the pollution travels across national boundaries. It should be noted that, in order to provide greater incentives to manufacturers, the EPA has exempted upstream emissions from consideration for battery charging, for the span of 2012 to 2016.

Fuel-Cell Vehicles

The other possible source of electric power for automobiles is a hydrogen-powered fuel cell. Hydrogen fuel-cell stacks in FCVs require significant amounts of precious metals, whose recycling and disposal also need to be taken into account. Hydrogen can be produced from a variety of sources. At present, the majority of hydrogen (primarily for nontransportation use) worldwide is produced from natural gas via steam methane reforming. The National Research Council has outlined possible hydrogen sources that would support a major transition from petroleum based liquid fuels to hydrogen for road vehicles (National Research Council 2008). They anticipate that early introduction would be through distributed natural gas reformers and possibly some distributed electrolysis, which do not require high-pressure hydrogen gas distribution infrastructure. The well-to-wheels CO_2-emissions reduction using distributed natural gas reforming would be less than one-half that from using gasoline in conventional internal combustion engines. CO_2 emissions using average U.S. electricity to generate hydrogen are greater than using petroleum-based fuels. As demand increases, large central natural gas or coal gasification reforming with pipeline distribution would develop. CO_2 emissions associated with coal utilization are about twice those of natural gas. CCS would be necessary for both of these sources to constrain CO_2 emissions. In the longer term, very low carbon technologies, such as gasification of biomaterials, thermochemical processes using nuclear or solar energy, photobiochemical and photoelectrochemical methods, and centralized electrolysis using renewable electricity may evolve.

CHAPTER 4. NEW FUELS

Gasoline, produced by the refining of crude oil or petroleum, is by far the major fuel used for transportation in the United States and most other countries. Total petroleum consumption in the United States is approximately 19 million barrels per day or 378 billion gallons per year (GPY) (U.S. Department of Energy 2010). The United States consumes about 280 million gallons per day or 137 billion GPY of motor gasoline. Motor gasoline represents about two-thirds of all energy used for transportation, one-half of all petroleum consumption, and about one-fifth of total U.S. energy consumption. The United States is a net importer of petroleum, with imports accounting for nearly 57% of the total consumption. Although Canada is the largest U.S. supplier of crude oil, the United States also depends on many other countries to meet its demand.

In 2007, the U.S. Congress passed the Energy Independence and Security Act (EISA; U.S. EPA 2007b). Among the many provisions of EISA, the following are important for the transportation sector: "to move the United States toward greater energy independence and security, to increase the production of clean renewable fuels, . . . [and] to increase the efficiency of . . . vehicles" (U.S. EPA 2007b). For renewable fuels, the law mandates increased production of biofuels, to reach 36 billion GPY by 2022; this includes 21 billion GPY derived from so-called advanced feedstock, not produced from corn sugar.

Some 10.6 billion gallons of ethanol were produced in the United States in 2009, including 0.6 billion gallons of advanced biofuels (Renewable Fuels Association 2010; U.S. EPA 2010d). This appears to be in compliance with the Renewable Fuels Standard (RFS) program promulgated by the EPA. Recently, EPA has proposed RFS2 for the 2011 calendar year (U.S. EPA 2010b). This proposed rule projects total 2011 renewable fuels consumption of 14 billion gallons (including 0.8 billion gallons of biomass-based diesel). Finally, EISA includes language to ensure that indirect effects of biofuel production are included in the calculation of overall (or life-cycle) GHG emissions for qualified renewable fuels. It should be noted that the law does not require similar analyses for petroleum fuels. The California Air Resources Board has also taken various steps to reduce the carbon intensity of motor fuels (California Air Resources Board 2010b).

Biofuels come in two general forms. The first — typified by ethanol and fatty acid esters — are oxygenated compounds that are dissimilar to the compounds found in petroleum based fuels. There are questions about the maximum level to which they may be mixed with conventional petroleum fuels without causing any negative effects on the materials used in engines, fuel systems, or emission-control devices. The second type is represented by biofuels that are hydrocarbon mixes which are quite similar to their petroleum based counterparts. Hydrogenated vegetable oil and Fischer-Tropsch (F-T) diesel are examples of the second type of biofuels. Their advantage lies in that they can be easily substituted for petroleum, both in the existing infrastructure and with engine components, and therefore there may be a transition from the oxygenates to hydrocarbon fuels in the future. Both types of biofuels are being developed in the United States and abroad and both are discussed in this chapter.

SPARK-IGNITION FUELS

Gasoline

In the course of the outlook period in question — approximately the next 10 years — traditional gasoline will in all likelihood continue to occupy the dominant role in fueling LDVs in the United States and in the rest of the world. The composition of the hydrocarbon portion of gasoline will probably not undergo major changes in the United States and Europe. Sulfur has already been reduced significantly in the United States and Europe (30 ppm average and 10 ppm maximum respectively). These extremely low levels allow sophisticated aftertreatment systems to operate efficiently over the lifetime of the vehicle. It is possible that there will be consideration of additional reductions in sulfur levels. In the United States, benzene concentrations in gasoline will drop to 0.62% by weight (national average) by 2011 (U.S. EPA 2007a). In other parts of the world, lead will be eliminated, sulfur levels will continue to drop, and benzene content may be reduced to reflect concerns about toxics emissions.

If there are major reductions in fuel demand for LDVs, then gasoline composition may be modified to reflect a rebalancing of refinery operations. Such reductions in gasoline demand might result from the widespread introduction of BEVs, a major increase in fuel economy, reduction in driving, or a major increase in the use of alternative fuels. One possible outcome of reduced gasoline demand at oil refineries would be for heavier gasoline molecules to be diverted to diesel fuel. The amount of heavy hydrocarbon molecules in gasoline would be reduced, probably making it a bit cleaner from an emissions perspective. While the outcome of these changes on fuel composition is difficult to predict, the large base population of vehicles and their longevity make it likely that these changes will occur gradually over a period of 10 years or more.

Ethanol

In response to many of the factors cited in the introduction, it is likely that the ethanol content of gasoline used for transportation in the United States will increase in the coming years. As mentioned above, the EISA of 2007 mandates 36 billion GPY of renewable fuels by 2022. At this time, almost all the gasoline sold at the pump in the United States contains 10% ethanol by volume. The California Air Resources Board has recently proposed using E10 gasoline as the certification fuel. Current U.S. ethanol production is 10.6 billion GPY (Renewable Fuels Association 2010) and is projected to grow.

In response to a request from a group of ethanol manufacturers, the EPA has recently proposed that it would allow the selling of E15 gasoline for use in newer vehicles (model year 2007 and later) (U.S. EPA 2010c). EPA's decision about the use of E15 in model year 2001 to 2006 vehicles is pending the availability of more data. Since this decision represents the first of a number of steps that will be necessary on the part of federal and state governments as well as the industry, and since this policy is likely to require separate E15 pumps, the commercial availability of E15 may well take some time.

There are serious questions about the suitability of higher concentrations of ethanol in gasoline blends for on-road and nonroad applications (such as issues related to drivability, operability, and materials compatibility), and some states are concerned that higher ethanol levels will put an additional burden on them with respect to air pollution mitigation (because of increased NO_x and evaporative and permeation emissions of ethanol and hydrocarbons). Thus, the challenges to the use of ethanol for transportation are related to the additional cost — for new as well as existing vehicles — of modifications to make the engines compatible with a higher percentage of ethanol and control of evaporative emissions (the latter as a part of mitigation strategies). In principle, these problems can be overcome. For example, Brazil has used high ethanol concentrations for many years, and the current ethanol content in gasoline is as high as 26%; the vehicles in Brazil are appropriately modified to accept the higher content of ethanol. As ethanol concentrations increase, the composition of the hydrocarbon portion of the gasoline will need to be adjusted to account for the volume and quality of ethanol. For instance, the high octane of ethanol may allow for a reduction in aromatics and possibly benzene concentrations.

Increased concentrations of ethanol in gasoline affect both tailpipe emissions and permeation and evaporative emissions. The results of increased ethanol content on exhaust emissions are:

- Increased ethanol, acetaldehyde, and possibly NO_x emissions
- Decreased levels of emissions of hydrocarbons, CO, and aromatics including benzene
- Secondary atmospheric aerosols may also be reduced along with lower emissions of aromatic compounds.

The addition of ethanol to gasoline affects the volatility of gasoline and can increase evaporative emissions. Between 0% and 10% ethanol, there are significant increases in evaporative emissions (including permeation); above 10% ethanol, the impact of emissions is not as well defined. The estimated impact of 10% ethanol on on-road emissions is shown in Table 1.

Research is currently underway, sponsored chiefly by the EPA and the Department of Energy, and conducted by the Coordinating Research Council, to measure the impact of ethanol concentrations above 10% on all aspects of on-road and nonroad performance and emissions. The EPA's RFS2 mandates that much of the growth in biofuels should be from processes that achieve large reductions in GHG (U.S. EPA 2010b). The impact of producing large volumes of ethanol on land-use patterns is discussed below. Substantial effort is directed toward developing new feedstocks and processes to produce ethanol in an energy-efficient manner and reduce GHG emissions. To the extent that these innovations are successful, the drive to increase ethanol concentrations in gasoline will grow.

High concentrations of ethanol (up to 85%) may also be used in flexible-fuel vehicles that are specially designed to accommodate ethanol concentrations between 0 and 85%. At this time, only small volumes of E85 are sold in the United States and so far, no flexible-fuel vehicles have met California's stringent LEV III requirements; evaporative and

Table 1. Projected Changes in Emissions from E10 vs. E0 Gasoline[a,b]

Pollutant	Source	Percent Change in Pollutant Level
Exhaust HCs	EPA predictive models	−9.7
NO_x		7.3
CO	EPA mobile 6.2 vehicle emission model	−36
Exhaust benzene	EPA predictive and complex models	−39
Formaldehyde		2.3
Acetaldehyde		174
1,3-Butadiene		6.1

[a] Adapted from U.S. Environmental Protection Agency 2010b.

[b] Summer (July) conditions are assumed. E10 is gasoline blended with 10% ethanol; E0 is gasoline without any added ethanol.

permeation emissions are a major problem. If ethanol availability increases and suitable materials that are compatible with the higher alcohol content can be used while keeping such vehicles affordable, the use of E85 may become more widespread and the emissions implications of E85 may be more important. There is a great deal of emissions certification data on E85 in flexible-fuel vehicles, but not much research has been carried out to understand the relationships between fuel properties and in-use emissions. It is likely that E85 use will increase acetaldehyde and ethanol emissions. The optimal composition of the gasoline portion has also not been studied extensively. More emissions research in this area would be useful. Additionally, since flexible-fuel vehicles can be fueled by either regular gasoline or E85, it is likely that they will run on intermittent blends a significant fraction of the time. More emission testing on intermediate blends (for instance, E40) is needed.

Other Alcohols

Research is also being conducted to develop manufacturing processes to produce alcohols of higher molecular weight, such as *tertiary*-butanol and *n*-butanol from renewable resources, most likely through fermentation (U.S. Department of Energy 2009). These alcohols are more compatible with gasoline than is ethanol, and it is possible that they will be approved for use at higher concentrations than ethanol. Significant research must be carried out before these alcohols are commercially viable. There are little data on emissions from these alcohols in current and future vehicles.

The use of methanol-gasoline mixtures in spark-ignition vehicles has a number of technical challenges. Methanol has even lower energy density than ethanol. It is not particularly miscible with gasoline and is prone to phase separation in the presence of small amounts of water — more so than ethanol. The U.S. EPA has approved use of low methanol concentrations in gasoline (< 5%) when accompanied by co-solvents such as *tertiary*-butanol. High levels of methanol in gasoline require specially designed cars. Methanol itself is well known for its neurotoxicity, and methanol use as a fuel can result in high emissions of formaldehyde, a toxic pollutant. Finally, methanol is usually made from natural gas or, in China, from coal. If made from coal, the carbon footprint for methanol fuel may be high. Increased methanol use in the United States is not likely to happen within the outlook period, the next decade. China is now the world leader in methanol production and a significant amount of methanol finds its way into the gasoline pool. The probability of increased use of methanol is low in the United States, Europe, and Japan, and medium in other parts of the world such as China and India. It should also be noted that, in addition to its direct use as a transportation fuel, methanol has uses in producing other fuels; for example, in the production of biodiesel and possibly as a source of hydrogen for fuel cells.

Natural Gas

Natural gas may be used in transportation in a number of ways: it may be stored as compressed natural gas (CNG) or liquefied as in liquefied natural gas (LNG), and burned directly in spark-ignition engines. It may also be converted to a liquid hydrocarbon fuel through chemical processing such as Fischer-Tropsch reactions (discussed below). With the advent of sizeable recoverable deposits of natural gas in the United States and elsewhere, an increase in the use of natural gas — especially for power generation — is expected (Massachusetts Institute of Technology 2010).

CNG is a clean fuel for spark-ignition engines and its low carbon content makes it attractive in terms of CO_2 emissions. It is used in many vehicles around the world, most notably in Italy and Argentina, and use is on the increase in China. Widespread use in the United States would entail a large investment in infrastructure for distributing and compressing CNG. Specially modified vehicles would be sold with high-pressure storage cylinders. Devices that store large amounts of CNG at lower pressures, possibly adsorbed on a substrate, are desirable but not currently available. Most CNG use in the U.S. transportation system today is in captive fleets with central refueling stations, and of these, most are composed of HDVs, such as municipal buses where the size of high-pressure tanks and the distribution issue are not serious detriments. Conversion of gasoline vehicles to CNG is possible, but is also quite expensive in the United States.

Whereas most data on CNG use are with older technology, nonmethane hydrocarbons and CO emissions associated with CNG are low. However, NO_x emissions may be equal to or a little higher than a gasoline-fueled counterpart, but lower than a diesel engine; PM emissions are low. In a study with buses powered by CNG, nanoparticle emissions from vehicles without a DOC were reported to be about the same as for buses equipped with a CRT; such emissions are suspected to arise from lubricating oil (Holmen and Ayala 2002). Formaldehyde emissions may be higher than for gasoline and diesel engines, while other toxic emissions are generally low. Methane emissions are higher than for gasoline- or diesel-fueled vehicles; furthering the design of CNG vehicles with low emissions is an area of active research and development.

From a GHG perspective, natural gas may also be used as a replacement for coal in generating electricity. This use of natural gas is a lower investment strategy than its use as an automotive fuel, which would require large infrastructure capital investments. It should be noted that methane itself, the main constituent of natural gas, is a potent GHG (approximately 20-fold more potent than CO_2), and care must be taken to minimize leakage during production, distribution, and use.

New supplies of natural gas in the United States are being obtained by shale drilling; this process requires hydraulic fracturing, or "fracking," the rocks with water and certain chemicals under high pressure. There are considerable environmental and health concerns associated with fracking (Kerr 2010) that are currently being investigated by the U.S. EPA and others.

Liquefied Petroleum Gas

Liquefied petroleum gas (LPG), which consists primarily of propane, is used in vehicles in plants and warehouses. LPG is a relatively clean fuel, but is available in only fairly small volumes; the outlook for substantially increasing the supply is not optimistic.

COMPRESSION IGNITION FUELS

Petroleum Diesel

Traditional, petroleum-based diesel fuel is expected to represent the majority of diesel fuels during the next 10 years and its composition will probably not change in the United States and Europe. In the United States, growth in the use of diesel engines to power LDVs could have an effect on diesel composition because refineries would be modified to produce a higher fraction of diesel relative to gasoline. The resulting changes in composition and emissions should be studied if this scenario is deemed likely.

Sulfur is a major source of particulate and acidic emissions but on-road sulfur levels in fuel sold in the United States and Europe have declined dramatically in recent years. U.S. EPA regulations reduced sulfur in diesel fuel from about 2000 ppm to 500 ppm in 1995 with further reductions to 15 ppm in 2006; these stringent standards have now been extended to nonroad fuel as of June 2010. In Europe, the current sulfur specification for diesel is 10 ppm.* These reductions have reduced PM emissions, and enabled the introduction of catalytic aftertreatment systems in light- and heavy-duty diesels. However, the lack of availability of low-sulfur diesel is a major barrier to the wide scale deployment of diesel emission control devices in developing countries.

A great deal of research is currently devoted to the development of HCCI engines in order to improve efficiency and reduce emissions relative to typical diesel engines. At this stage of development, it is not possible to define with any certainty the fuel requirements of these engines. It has been suggested that the best fuel will be a minimally refined product that has properties midway between gasoline and diesel. The emissions effects associated with fuels for HCCI engines cannot be estimated at this time. It is important to follow the development of HCCI engines and make a determination if future emissions research is warranted.

Two significant sources of new diesel fuel blendstocks — or fully formulated fuels — are F-T processes (sometimes referred to as synthetic diesel) and fatty acid esters (commonly called biodiesel).

Fischer-Tropsch Diesel

F-T diesel is produced generally by a process consisting of two steps. First, a feedstock is thermally treated to produce a synthesis gas consisting primarily of CO and hydrogen. In the second step, the synthesis gas is reacted catalytically to produce a mixture of hydrocarbons, the composition of which may be adjusted by choosing reactor design and reaction conditions. Most commercial processes produce either diesel fuel or lubricant base stocks. Raw F-T fuel is usually upgraded to improve quality by hydrocracking and hydro-isomerization creating isoparaffins from normal paraffins and/or removing waxy materials to improve cold flow performance. The resulting fuel is similar to petroleum diesel in molecular weight range (C_8–C_{24}), although the distributions may not match exactly. The F-T diesel fuel is extremely high quality and has low or zero aromatics and sulfur, along with a very high cetane number (>70) (Alleman and McCormick 2003). F-T diesel produced from the hydroprocessing of F-T waxes has lower energy density. It also has somewhat poorer lubricity than conventional diesel because lower molecular weight (C_4–C_{12}) aliphatic alcohols, which have excellent lubricity qualities, are destroyed during hydrorefining. The addition of small quantities (~200 ppm) of lubricity additives can overcome this poor lubricity (Norton et al. 1998). Catalysts and associated unit processes have been developed recently that directly produce a high-quality F-T diesel that does not require hydroprocessing and isomerization. This fuel has been shown to have better lubricating properties than conventional diesel (Ayasse 2009; Berlowitz et al. 1997; Ding et al. 2004).

F-T diesel has been shown to reduce emissions from diesel engines significantly. In one study of a heavy-duty diesel engine, emissions relative to petroleum diesel were reduced by 40% for PM, 20% for NO_x, 41% for hydrocarbons,

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* The 15-ppm sulfur limit in the United States is at the pump and includes sulfur from pipeline and truck transfer. The 10-ppm sulfur limit in Europe is at the refinery gate and does not include sulfur from transfer, so the two numbers are not directly comparable. In practice, sulfur levels in the United States and Europe are similar and quite low.

and 30% for CO (Fanick et al. 2001). These reductions are consistent with the properties and composition of F-T diesel (Hochhauser 2009). In a test of a European light-duty diesel passenger car, a 50/50 mixture of conventional and F-T diesel reduced emissions of hydrocarbons and CO by about 45% and PM emissions by 22%. NO_X emissions were not affected (Schaberg et al. 2005). The benefits for reducing emissions of hydrocarbons, CO, and NO_X suggest a nonlinear benefit for the mixtures. More emissions data in heavy-duty diesels with modern aftertreatment devices would be useful.

Various feeds may be used to produce F-T diesel — natural gas, coal, shale, and biomass. Fuel that has properties similar to F-T diesel may also be produced by processing vegetable oil in a refinery; the end result is commonly called hydrogenated vegetable oil. The carbon footprint of these processes and feedstocks is discussed in a later section.

A number of commercial plants to produce F-T diesel from natural gas and coal are in operation; others are being studied or planned. Natural gas produced in remote locations that cannot be distributed with the existing pipeline infrastructure may be put to other uses such as those for shipping after liquefaction or F-T conversion. LNG would probably be used as a fuel to produce electricity or for home heating in the United States. Production of F-T diesel using biomass as a feedstock is likely to take place in smaller plants with locally grown biomass.

The most likely use of F-T diesel will be as blendstocks in standard diesel fuel. Use of F-T diesel as blendstocks allows fuel manufacturers to increase diesel production without the expense of marketing a totally new fuel. If engine manufacturers develop new engine technology that takes advantage of the special properties of F-T diesel, then a separate grade of fuel would have to be produced, distributed, and marketed.

The ASTM International is developing new specifications (ASTM 2009) for diesel fuel derived from the low-temperature F-T process. These specifications will deal with test methodologies and terminology for such synthetic fuels. Through this process, ASTM will address the suitability of these fuels as a blend component in fuels conforming to the D975 standard, and this specification will be used to ensure that purchasers obtain genuine synthetic diesel fuel of high quality, which offers lower exhaust emissions capabilities when used in current and advanced compression ignition engines.

Biodiesel

Biodiesel refers to esters of fatty acids. These are usually fatty acid methyl esters, but may also be ethyl esters. Plant oils such as soy, palm, rapeseed (canola), and jatropha consist primarily of triglycerides. Biodiesel is produced from the transesterification of these oils with alcohol, usually methanol. When purified, the resulting product contains oxygenated molecules that have a relatively narrow molecular weight distribution in the diesel fuel range. Research is also being conducted to produce fatty acids from algae farming. Glycerin is a significant byproduct of biodiesel production, and research is underway to find new uses for this product. The methanol used for transesterification is generally produced from natural gas or coal, and is thus not obtained from biologic sources.

Relative to petroleum-based diesel fuel, fatty acid methyl esters have a number of benefits and challenges, which are summarized in Table 2.

The negative aspects of biodiesel performance can be overcome through blending or the use of additives or both.

While it may be used neat, biodiesel is most commonly used as a blendstock. ASTM International has developed a specification for pure biodiesel (2010a), and 5% (volume) biodiesel (B5) is approved for use under the diesel specification (D975). ASTM has developed a specification for higher concentrations, B6-B20 (ASTM 2010b). Use of biodiesel is expected to grow in the outlook period, in part in response to the mandates contained in EISA 2007.

The emission effects of biodiesel have been studied and U.S. EPA has published a summary of emissions data along with a regression model (U.S. EPA 2002, 2010b). The data in Table 3 show that biodiesel reduces emissions of PM, hydrocarbons, and CO and somewhat increases emissions of NO_X. Predicted emission effects in heavy-duty diesels are shown below for a 20% (volume) concentration of biodiesel (B20) in typical diesel fuel. Other studies have reported similar effects (Hoekman et al. 2009; Robbins et al. 2009).

Table 2. Comparison of Biodiesel with Petroleum Diesel: Properties and Performance

Advantages of Biodiesel	Disadvantages of Biodiesel
Lower emissions of PM, HCs, CO, and PAHs	Slightly higher emissions of NO_X and possibly aldehydes
Near-zero sulfur content, without need for desulfurization	Higher viscosity
Lower aromatic content	Poorer low-temperature properties
Better lubricity	Poorer oxidative stability
Higher cetane number	Susceptible to microbial growth
Lower GHG emissions (on life-cycle basis)	Lower energy content
	Increased engine deposits

Table 3. Changes in Emissions with the Use of B20 vs. B0 Diesel[a,b]

Emissions	Percent Change
NO_x	+2
PM	−16
HCs	−14
CO	−14

[a] Adapted from U.S. Environmental Protection Agency 2010b.

[b] The table shows the impact on emissions, for all cycles, of using fuel with 20% soybean-based biodiesel by volume (B20) compared with an average diesel fuel containing no biodiesel (B0).

Because conventional diesel fuel is highly paraffinic and biodiesel fuels contain esters, it is possible that unregulated emissions will be affected. Based on the particular vegetation source used to produce the biodiesel fuel, emissions of formaldehyde and acetaldehyde may increase, as compared with a petroleum diesel (Hansen and Jensen 1997). Although quantitative information on these effects has not been published, one possible effect would be an increase in aldehyde emissions, because of the higher oxygen content of the biodiesel. More research in this area will be useful.

Alcohols and Ethers

Alcohols and ethers have been proposed for use in diesel engines, either neat or in mixtures with diesel fuel. Alcohols such as methanol and ethanol are not particularly miscible with diesel fuel and their use is unlikely within the outlook period of the next decade. Ethers such as dimethyl ether (DME) can be good diesel fuels, but there does not seem to be a large incentive to introduce them into the diesel pool. DME is also highly volatile and flammable; its physical properties are similar to propane. Its widespread use in transportation would require expansion of the LPG infrastructure to transport and store it. There is interest in DME use in Asia and some plants are being built in China and Japan. Coal and natural gas are the primary feedstocks for DME production. DME can also be produced from the thermochemical conversion of biomass to produce synthesis gas, which is then followed by the catalytic conversion of the synthesis gas to DME. Unlike any other synthetic diesel fuel, DME virtually eliminates soot emissions and the need for DPFs.

SOURCE-RELATED ISSUES CONCERNING FUELS

High oil prices have driven interest in a variety of transportation fuel sources that are not petroleum based but based on other sources of fossil fuels. These fuel sources include tar sands, oil shale, and liquefied coal. The production and use of these fuels could increase air and water pollution and damage sensitive ecosystems, although some of this environmental impact could potentially be mitigated through better regulation and enforcement (Bordetsky et al. 2007). As discussed in the next section, use of these sources may also increase global GHG emissions.

Oil Sands

Currently, U.S. oil consumption is about 20 million barrels per day; 1.4 million barrels per day of crude oil are produced from the oil sands in Alberta, Canada, of which two-thirds is exported to the United States. According to the Canadian Association of Petroleum Producers, oil sands production is expected to grow and reach three to four times current levels by 2020 (Canadian Association of Petroleum Producers 2008). Oil sands consist of a mixture: 85% sand, clay, and silt; 5% water; and 10% crude bitumen — a tarlike substance from which oil can be extracted. Oil sands are obtained either by strip mining or by injecting steam into the earth to release bitumen (the in situ production process). Canada and Venezuela have the largest deposits of oil sands in the world, and oil sands are the fastest growing source of CO_2 emissions in Canada (Grant et al. 2009).

Since the composition of crude produced from oil sands is different than conventional crude, the composition of fuel produced from oil sands may also be different. It is likely that diesel fuel produced from oil sands will contain more naphthenes than diesel produced from conventional crude oil; the effects on the composition of gasoline are less certain. An investigation of how fuel from oil sands may be different would be useful in understanding potential emissions and health effects. A joint program of government and industry in Canada compared emissions from heavy-duty diesel engines operating on fuel derived from oil sands and those from conventional crude (Mitchell 2000). No impact of the fuel from the crude source on emissions was seen. However, the fuels were specially blended to have matched properties, such as aromatic content. Differences in composition that might be reflected in actual blending may not be reflected in the results of the Canadian program. In addition, the tendency of these fuels to form secondary organic aerosol is poorly understood. This area deserves more investigation.

Production of crude from oil sands generates air and water pollution, negatively impacts the ecosystems of boreal forests (Grant et al. 2009; Bordetsky et al. 2007), and uses large amounts of water. In addition, the holding reservoirs for wastewater are a suspected source of contamination, posing threats to humans, wildlife, and wetlands (Tenenbaum 2009). The high concentrations of pollutants such as naphthenic acids and heavy metals are acutely toxic to aquatic life (Bordetsky et al. 2007).

Oil Shale

Oil shale, a rock found in Wyoming, Utah, and Colorado, produces oil when heated to very high temperatures (pyrolysis). According to a RAND study, under a high-growth scenario, "an oil shale production level of 1 million barrels per day is probably more than 20 years in the future, and 3 million barrels per day is probably more than 30 years into the future" (Bartis et al. 2005).

The development of commercial oil shale production is an energy-intensive process and could increase air pollution (Bartis at al. 2005). Toxic elements such as arsenic and selenium could be released in the production process and might leach into the Colorado River watershed system. Additional sources of power — using coal, natural gas, or oil shale — would likely be needed to produce oil from shale and, depending on the fuel used for such processes, they could generate dangerous air pollutants, including SO_2, NO_x, and mercury.

Coal Gasification

Conversion of coal to gasoline is also being considered as a potential solution to supply and cost issues while also addressing concerns about energy security. Although this conversion process has been in existence for many years, first used by the Germans in World War II, current market conditions have led to strong and renewed interest in this technology and there are now active plans to construct new liquid-coal plants. According to the RAND study cited in the discussion of oil shale, coal-to-liquid production could reach as high as 3.5 million barrels per day by 2030 (Bartis et al. 2005).

The effect of coal-to-liquid production on the environment and on public health includes the known effects associated with coal extraction (including air and water pollution), CO_2 emissions, and the large amounts of water required in the production process (Bordetsky et al. 2007). The effects of coal extraction and its use on the environment and on health include landscapes destroyed by mountain-top removal and scarred by strip mining; air emissions containing acidic, toxic pollution from coal combustion; and water pollution caused by coal mining and combustion waste products (Bordetsky et al. 2007).

CROSS-CUTTING ISSUES

Climate Impact and Life-Cycle Analysis for Fuels

Alternative fuels were promoted in the 1980s as beneficial in terms of both air quality and energy security. As gasoline and diesel became cleaner and emission controls of internal combustion engine vehicles dramatically improved in the 1990s, the air quality benefit of alternative fuels over gasoline and diesel gradually diminished in comparison. Since the late 1990s, alternative fuels, especially biofuels, electricity, and hydrogen gas, have been promoted for their energy-security benefits and GHG emission-reduction benefits, especially in the United States. Some fuel pathways, such as coal-to-gasoline conversion, are associated with significant environmental issues.

The production and use of alternative fuels in place of petroleum gasoline and diesel changes the amount of emissions during both fuel production and utilization, and may shift emission locations upstream from vehicle tailpipes to the fuel production and distribution stages. The changes and the shift in the location of emissions along the entire fuel cycle demand that a life-cycle analysis (LCA) of fuel–vehicle systems be conducted so that the environmental effects of the systems can be evaluated in a holistic and consistent way. Since the 1990s, several comprehensive LCA models have been developed in North America and Europe to examine the energy and emission effects of fuel and vehicle systems. These models generally address emissions of criteria pollutants and GHGs, and the use of energy from different sources. One such model is the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model developed at Argonne National Laboratory with the support of the U.S. Department of Energy. The results of emissions models can be fed into emission-inventory models, air-quality models, and eventually health-effects models (though the LCA models themselves do not address health effects). Figure 1 presents sample results from the GREET model of petroleum use and GHG emissions from a group of fuels used in different vehicle technologies (Wang and Huo 2009).

In Figure 1, the *y*-axis shows changes of petroleum use of different fuels relative to petroleum gasoline, representing potential energy-security benefits of alternative fuels. The *x*-axis shows changes of CO_2-equivalent emissions (including CO_2, methane, and N_2O) relative to petroleum gasoline. Petroleum gasoline and diesel in hybrid electric vehicle (HEV) applications realize reductions in petroleum use because of efficiency gains of HEVs. LPG use in internal combustion engines does not eliminate petroleum use, since about 40% of LPG in the United States is derived from petroleum. Other nonpetroleum fuels have large petroleum reductions. GHG emission effects vary widely among the alternative fuels. Dimethyl ether (DME), F-T diesel, and methanol (MeOH) from coal without CCS result in doubling of GHG emissions relative to petroleum gasoline. With CCS employed, GHG emissions associated with coal-derived fuels are equivalent to those of petroleum diesel. Fuels derived from natural gas such as CNG, DME, MeOH, and F-T diesel have small reductions or no changes in

GHG emissions. Natural gas-based hydrogen for FCV applications results in significant reductions. For EVs, GHG benefits depend on electric generation mix. The Chinese generation mix with 80% of electricity from coal results in small reductions; the U.S. mix with about 50% of electricity from coal results in moderate reductions; and the cleaner California mix results in large reductions. Biofuels (ethanol, biodiesel, F-T diesel, and hydrogen) in general, especially those produced from nongrain feedstocks, result in huge GHG reductions.

Several key issues are being addressed in fuel LCA. Whereas biofuels are being promoted for GHG emission mitigation, their effects on overall GHG emissions have been the subject of heated debate. In the past several years, studies were conducted to address indirect land use changes from large scale biofuel production. Direct land use changes are those changes that are needed for cultivating feedstocks for biofuel production; indirect land use changes refer to changes that occur somewhere beyond biofuel feedstock growth regions. In principle, indirect land use changes occur because changes in global supply and demand of food resulting from biofuel production lead to the cultivation of new land for food production. There is increasing acceptance of the indirect land use changes related to large-scale biofuel production (Searchinger et al. 2009; Searchinger 2010), although debate continues on the exact magnitude of such effects and the best way to estimate them (Tyner et al. 2010). Thus, caution should be exercised when considering the impact of diverting a large amount of agricultural land to crops for biofuel production and whether, on balance, a particular biofuel is associated with more or fewer GHG emissions than petroleum. In addition, the expansion of food-crop or nonfood-crop production for future biofuel could also have a negative impact on water quality and could damage sensitive ecosystems (including the Gulf of Mexico through hypoxia) (Costello et al. 2009).

It should also be recognized that the U.S. crude supply has a large — and increasing — share of Canadian oil sands and Venezuelan heavy, sour crude. Production of these fuels is energy and emission intensive, as discussed elsewhere in this report.

Coal-based fuels such as MeOH, DME, and F-T diesel are promoted in countries such as China for benefits related to energy security. China currently produces a large amount of MeOH from coal, some of which is legally (and illegally) blended into gasoline. Liquid-fuel production from coal involves coal gasification (or liquefaction) and fuels synthesis, two major processes that are capital and energy intensive. These processes also consume a substantial quantity of water.

Fuel Additives

One of the greatest environmental successes of the late twentieth century is the phaseout of lead additives in most gasoline around the world. Lead was once widely used as an octane enhancer in gasoline because it was readily available and cost-effective. Over time, lead additives were removed, as our understanding of the neurotoxicity of lead, especially for children, improved. Today, unleaded gasoline is used exclusively in all but about 17 countries.

The technical options available to replace lead for octane enhancement include:

- Refinery modifications or redesign and the use of selected crude oils or high octane blendstocks; and
- The use of metallic octane-enhancing additives, oxygenates, or both, and including alcohols and ethers.

Because of the cost of refinery modifications, many refiners, especially those in the developing countries, have opted for metallic additives such as methylcyclopentadienyl manganese tricarbonyl (MMT) and dicyclopentadienyl iron (ferrocene) to replace lead. The use of metallic additives is attractive because of their lower cost, ease of use, and the flexibility in octane adjustment they provide refiners. MMT and ferrocene do not require special handling equipment and can be added to gasoline with existing additive injection equipment. Use of these metallic additives does not affect other gasoline properties. However, they do raise concerns regarding health effects and, in some cases, aftertreatment systems. The presence of MMT and ferrocene in gasoline leads to the formation of solid, nucleation mode particles, primarily < 10 nm diameter nanoparticles (Gidney et al. 2010). These particles fall well below the 23 nm cutoff of the anticipated Euro 6 particle number standard.

The combustion of MMT releases manganese compounds into the air. The inhalation of high concentrations of such compounds has been shown to produce symptoms that are akin to those of Parkinson's disease. Although data on low-level exposure to such compounds — as will be generated from their use as fuel additives — are sparse, there is concern that at low levels, health effects may take a longer period of time to develop, making detection and treatment more difficult. Because of concerns regarding the neurotoxicity of manganese compounds, the California Air Resources Board banned the use of MMT in unleaded gasoline in 1976 (see California Air Resources Board 2005). Although the U.S. EPA has not banned the use of MMT in conventional gasoline, there is little or no use in the United States or most other industrialized countries. Its use continues in some developing nations, especially those in Asia (including China) and Africa, which is a cause for concern among international health experts. The literature

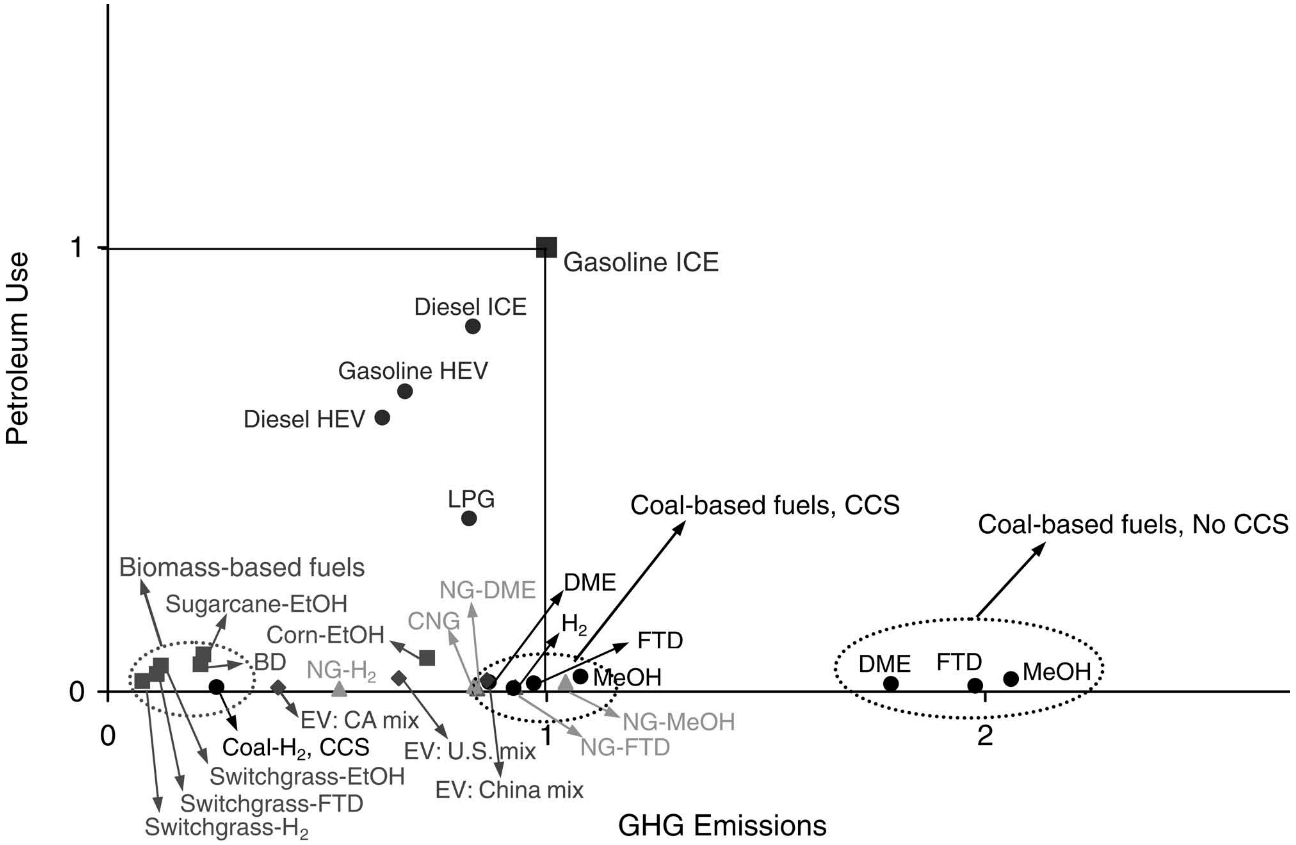

Figure 1. Relative Changes in Petroleum Use and GHG Emissions by Vehicle–Fuel Systems. Values are based on per-km results. BD denotes biodiesel, CA California, EtOH ethanol, FTD Fischer-Tropsch diesel, H_2 hydrogen, ICE internal combustion engine, and NG natural gas. See text for further explanation. Reprinted from Wang and Huo 2009, with the permission of Springer Science and Business Media.

on health and policy issues regarding the use of MMT has been reviewed by several organizations; for a recent review, see a report from the International Council on Clean Transportation (Minjares and Walsh 2009).

There is extensive literature on the occupational effects of exposure to ferrocene at levels much higher than the ambient levels expected from its use as a fuel additive. The investigation and analysis of the health effects associated with ferrocene has, however, been less rigorous than other, more widely used additives. Like other metallic additives, ferrocene is not widely used in the United States.

Vehicle manufacturers, who are responsible for maintaining low emissions for the lifetime of the vehicle through durable and effective operation of their emissions control systems, are concerned that metallic ash-forming additives can adversely affect the operation of catalysts and other components, such as oxygen sensors, in an irreversible way that will increase emissions. Thus, there appears to be little interest in the United States and other developed countries in the use of metal additives at this point.

Ethers such as methyl *tertiary*-butyl ether (MTBE) have been used in gasoline in the United States since the 1970s to reduce exhaust emissions and to increase octane. There are serious concerns about MTBE contaminating groundwater and drinking water, where it is easily detected by smell and taste at concentrations as low as 10 to 20 parts per billion. Concerns have also been raised about the effects on human health of exposure to MTBE. These ethers also do not biodegrade easily. As a result, MTBE and other related ethers (ethyl *tertiary*-butyl ether and *tertiary*-amyl methyl ether) are banned in California and are no longer used in the rest of the United States. However, ethyl *tertiary*-butyl ether is commonly used in Europe, especially France.

CHAPTER 5. OTHER EMISSIONS ISSUES

As new technologies and fuels discussed in this paper decrease the overall emissions of PM from the tailpipe and other sources, noncombustion emissions of PM are receiving more attention, for example, dust from brake and tire wear, lubricating oil products and resuspended road dust (HEI Panel on the Health Effects of Traffic-Related Air Pollution 2010). PM from such sources makes up an increasing proportion of total vehicle-related emissions and is of particular concern for those living in heavily populated urban areas and close to major roads and highways. Such emissions contain metals and organic compounds that are of potential health concern. Although these sources of PM are not emerging technologies in the same sense as the others in this report, the Committee believes that they merit attention.

Engine lubricants also affect pollutant emissions from automobiles. By improving engine efficiency, lubricants help reduce CO_2 emissions and thereby GHG emissions. On the other hand, all engines consume some amount of lubricating oil, with the amount depending on factors such as oil volatility, engine maintenance, age and design. In addition, some components of the oil evaporate and break down during use. The resulting byproducts can be directly emitted and may also affect emission control systems. Historically, the lubricant contribution to emissions from well-designed and maintained vehicles and engines has been relatively low and has been steadily decreasing. However, the advent of cleaner fuels, such as ultra-low sulfur diesel fuel, and new low emission technologies, may make the lubricant's contribution more important on a relative basis.

BRAKE WEAR

Description of the Technology Brake lining is composed of five major components: binders; fibers; fillers; modifiers; and abrasives (Filip and Wright 1997; Filip et al. 1997; Kennedy et al. 2002). Binders are resins — typically made of phenol formaldehyde — which act to solidify the matrix. Fibers are randomly interwoven throughout the matrix and often overlap to provide reinforcement, integrity, and strength to the composite; examples include ceramic, mineral, aramid, and cellulose fibers, and metal chips (e.g., copper, steel, brass). Fillers are low-cost materials used to occupy space, for example, barium and antimony sulfates, kaolinite clays, magnesium and chromium oxides, powdered stone, powdered metals, and a variety of other substances. Modifiers are used to optimize wear characteristics, by acting as lubricants or in other ways; examples of modifiers include graphite and some metallic fibers. Abrasives are used to increase friction; examples include silica, aluminum oxide, and zirconium silicate. However, brake composition is highly variable, often proprietary, and constantly changing.

Likelihood of Use and Time Frame Although specific formulations are not standard and change frequently, this technology is stable and not likely to change dramatically.

Emissions of Potential Concern Dust created from brake linings contains smaller particles than tire wear or resuspended road dust, and comprises organic and inorganic compounds. Examples of organic compounds present in brake linings include the polymer aramid and phenolic species, although such compounds and other organic compounds are likely to undergo thermal decomposition or transformation during vehicle braking. Many metals, some of which are toxic, are also present in the lining; examples include chromium, nickel, copper, manganese, and antimony (Garg et al. 2000). Some iron may also be worn from brake rotors of the braking system and become airborne.

The percentage of brake wear that becomes airborne is highly variable and has been reported as anywhere between 32% to 70% (Cha et al. 1983; Garg et al. 2000; Kennedy et al. 2002; Sanders et al. 2003). For the calendar year 2009, estimated California brake-wear emissions accounted for 18% of the annual average statewide PM_{10} emissions inventory and 10% of $PM_{2.5}$ (California Air Resources Board 2010c) (PM_{10} denotes PM with an aerodynamic diameter ≤ 10 µm, and $PM_{2.5}$ PM with an aerodynamic diameter ≤ 2.5 µm).

There has been some concern about the use of asbestos in brake lining, especially regarding exposure of people who may change brakes themselves (Occupational Safety and Health Administration 2006; U.S. EPA 2007c). In a recent study, the California Air Resources Board sampled 137 light-duty and medium-duty vehicles, ranging from 1984 to 2006 model years, and found only four vehicles (i.e., 2.9%) that had asbestos (chrysotile) in their brake lining; all were believed to be aftermarket products (California Air Resources Board 2010d). Fifty-four heavy-duty vehicles, ranging in model years 1990 to 2007, were subsequently sampled; no asbestos-containing brake linings were found in them.

In electric-drive vehicles, the presence of a regenerative braking system does not impact composition of the brake linings. Regenerative braking relies on a separate system, comprising an electric motor and motor controller. At some point during deceleration, the regenerative braking system switches over to the conventional braking system. Thus, it appears highly likely that there will be less brake wear in EVs.

Life-Cycle Issues Life-cycle issues include the exposure to toxic metals during mining and processing for the production of brake linings.

Specific Regulatory Issues PM generated from brake wear is receiving attention lately because of potential health and ecological effects, especially due to the presence of metals in such PM. The state of Washington recently banned the use of braking products that contain copper because of concerns about ill effects on fish. Other state-based general laws (for example, the California Green Initiative) may mandate evaluation of some materials. Another regulatory effort in California is Senate Bill 346, which was signed into law in September 2010 and sets *de minimis* levels (essentially a ban) of hazardous materials in brake linings sold in California. Limits are set for asbestiform fibers, chromium VI, cadmium, lead, mercury, and copper (State of California 2010). Based on the passage of SB 346 and the California Air Resources Board study discussed above, asbestos does not appear to be an issue in California. The magnitude of this problem outside California is not known. However, brake lining containing asbestos is sold in developing countries.

TIRE WEAR

Description of the Technology A typical tire has five major components: tread; sidewall; belts; body plies; and the bead. Tread is the portion of the tire in contact with the road, sidewall is the side of a tire, belts are layers of steel that run circumferentially around the tire under the tread, body plies are rubber-coated layers of textile cords that run perpendicular (radial ply) or at other angles (bias ply) to the tread, and the bead is a high-strength steel cable coated with rubber that sits along the inside of the tire allowing it to stay on the wheel rim.

Tire formulations vary with desired properties such as physical strength, wear resistance, driving type, and are proprietary (Rogge et al. 1993; Kennedy 2002; ChemRisk, Inc., and DIK Inc. 2008). In general, the major components of the tire are rubber (a mix of natural, polyisopropene, butadiene, and styrene-butadiene rubbers), carbon black, steel, and hydrocarbon oils and other components (Rubber Manufacturer's Association 2009). The following three components — rubbers, which provide structure; carbon black, which provides reinforcement and strength; and hydrocarbon oils, which are plasticizers — each make up 10% to 30% of tires. Silica is sometimes used as a partial substitute for carbon black, especially in low-rolling resistance tires, which can have up to 30% lower resistance than normal tires. A variety of other chemicals are also added, including several metals (particularly zinc), resins, antidegradants, cure activators and agents, accelerators, retarders, bonding agents, and bracing. The largest component of these are resins such as aromatic hydrocarbon polymers that also serve as processing aids and can account for up to 7% of tire composition.

Likelihood of Use and Time Frame Some 250 million tires are shipped annually in the United States, with some 80% used for replacement in existing vehicles. Rolling resistance typically consumes 4% to 7% of the total energy expended by vehicles and therefore reducing rolling resistance has been a priority for automobile and tire manufacturers (National Research Council 2006). With the exception of the increasing use of low-rolling resistance tires, tire technology is not likely to change much in the near future.

Emissions of Potential Concern The rate of tire-tread wear is quite variable and depends on the road and driving and tire conditions. Most tire-wear particles are coarse, with less than 10% being in the fine range and a large proportion settle close to the road. Various studies have placed the contribution of tire-wear particles to airborne PM at 1.6% to 10% of total suspended particles in the United States (ChemRisk, Inc., and DIK Inc. 2008). In addition, the impact of leachates of metal ions and the extraction of water-soluble organic compounds may be of environmental concern (Weckwerth 2001).

The majority of tire-wear emissions are carbon (ranging from 60% to 87% of total mass), with organic carbon accounting for two-thirds or more of the total carbonaceous mass (Hildemann et al. 1991; Kupiainen et al. 2005; Schauer et al. 2006). Organic compounds found in tire-wear particles include large amounts of *n*-alkanes like heptatriacontane, *n*-alkanoic acids like stearic acid, and natural resins like dihydroabietic acid. PAHs are emitted at a lower rate of approximately 226 µg/g particle sample but remain a health concern. Zinc represents 1% to 2% of tire emissions and is found in measurable amounts across tire brands and types (Weckwerth 2001). Smaller concentrations of other metals such as nickel, cadmium, and copper have been reported (Kochir 2010). It is not known how low-rolling resistance tires, which are becoming increasingly popular, affect wear emissions.

Life-Cycle Issues The major life-cycle issue is related to the disposal of used tires. In 2007, almost 90% of the scrap tires generated in the United States by weight were consumed in end-use markets, which comprise uses for tire-derived fuel, ground rubber applications, and civil engineering (Rubber Manufacturer's Association 2009). Open-air, uncontrolled scrap-tire fires are a major concern as they emit a number of organic and inorganic compounds. Scrap tires also serve as a breeding ground for vector-borne diseases.

Specific Regulatory Issues There are no U.S. regulations pertaining to tire materials, although in the European Union, Japan, and South Korea, regulations limit or prohibit the use of highly aromatic extender oils to control the release of PAHs.

LUBRICATING OIL

Description of the Technology Engine lubricating oil, composed of oil basestock and additives, has a variety of critical functions in an internal combustion engine, such as reducing friction and wear, removing debris and impurities, and preventing corrosion. By reducing friction, the oils also improve fuel economy and thereby reduce CO_2 emissions. With newer formulations used in LDVs, there can be as much as 2% or more improvement in fuel economy compared with older technology and lubricant formulations. During use, some components of the oil inevitably break down, dirt and sludge build up, some lower molecular weight compounds may volatilize, and oil viscosity increases. Because all these factors degrade the performance of the oil, it must be changed at regular intervals. Because of improvements in engine design and oil formulation, however, there is a trend toward increasing the mileage interval between oil changes.

The oil basestock used in making lubricating oil usually is derived from crude oil. Synthetic base oils may be used in higher quality lubricating oils in order to improve performance characteristics of the oils, such as longer drain intervals and increased wear protection. These synthetic base oils may be made from chemical feedstocks (such as poly alpha olefins), purified refinery streams, or the F-T process (using natural gas or biomass feedstocks). Among the advantages of the synthetic oils is that the change in their viscosity with temperature is low and that they are resistant to oxidative degradation.

A variety of additives is added to the base oils in manufacturing lubricating oil, including antioxidants, detergents and dispersants, viscosity improvers, anti-wear agents, antifoaming agents, and dispersants (for example zinc dithiophosphate, and compounds containing lead, copper, chromium, iron as well as a variety of organic and inorganic compounds). New compounds — often proprietary — are developed by various manufacturers on an ongoing basis to improve oil performance.

The American Petroleum Institute (API) categorizes basestocks and fully formulated engine oils in various groups, depending on composition and performance (API 2007). In Europe, categories for engine oils are defined by the Association des Constructeurs Européens d'Automobiles. As engine design and emission control technologies have evolved, new lubricant testing procedures and performance criteria have been developed that result in more complex, higher quality formulations.

Likelihood of Use and Time Frame Lubricants will continue to be used in all combustion engines for the foreseeable future, but the volume used annually may decline — even as the vehicle population grows — because many manufacturers are adopting longer drain intervals. LDVs are moving from 3,000-mile drain intervals to as much as once per year or 10,000 miles; some heavy-duty manufacturers allow up to 100,000-mile intervals when combined with an appropriate oil analysis program.

Changes in lubricant specifications and formulations tend to occur in parallel with changes in engine technology. The aftertreatment devices used with diesel engines are sensitive to the presence of metals and ash generated from the engine and lubricants; therefore, there is much interest in the development of lubricant oils with low levels of sulfur, phosphorus, and ash precursors. Other factors, however, such as new fuels and engine/vehicle technologies, could affect the degree to which oil contributes to emissions.

Emissions of Potential Concern As noted, lubricants can affect vehicle exhaust depending on factors such as engine and vehicle design, lubricant composition, engine age, driving conditions, maintenance and the fuel used (Kleeman et al. 2007). Even under the best circumstances, some engine wear is to be expected from abrasion of engine parts, and the products of such wear are taken up by the oil. Various constituents of the oil may also break down, volatilize or combust, adding to engine-out emissions.

Relatively little research has been done on the impact of lubricating oil on emissions. Some base oils may contain sulfur derived from their original source and which may be emitted from the tailpipe. Ash, derived from additives (containing compounds of, for example, sulfur, phosphorus, calcium, magnesium, zinc) or from wear of engine parts (containing iron, lead, copper, chromium) may also clog DPFs, decrease catalytic efficiency, and increase the toxicity of emissions. This is a particular problem for all diesel vehicles, although it is more acute for LDVs, which employ smaller DPFs that are generally not serviced during the vehicle's useful life. The challenge for both light- and heavy-duty applications is to reduce ash content without impairing other aspects of performance, especially now that extended intervals between oil changes are sought by manufacturers and customers of both light-duty and heavy-duty vehicles. Low ash in lubricating oils is a warranty requirement from diesel vehicle manufacturers for post-2007 engines in the United States so that the efficiency of aftertreatment devices is not compromised.

The impact of new fuels on oil-related exhaust has not been studied in much detail. Particle emissions from CNG-fueled vehicles are believed to derive from lube oil (Holmen and Ayala 2002). Other fuels, such as those containing increased ethanol and biodiesel, may interact with the oil and reduce its effectiveness. For example, certain diesel engines cannot tolerate biodiesel above 5% because the fuel gets into the oil more readily and decreases its lubricity, risking significant damage to the engine. The impact of the lubricant on evolving vehicle–fuel systems is likely to change over the coming decade, and ongoing research suggests a need to evaluate lubricants more closely as an emission factor.

The National Renewable Energy Laboratory is close to completing a detailed study on emissions related to lubricating oil. When published, the results of this study will provide much needed information in this area.

Life-Cycle Issues As noted, by improving engine efficiency, lubricating oils decrease CO_2 emissions. Other life-cycle issues are related to the source of base oil and additives. The overall volume of lube oil consumption, and therefore the volume of waste oil generated, is decreasing. Current research is focused on improving friction modifiers to increase fuel economy without losing oil durability or other performance benefits.

Specific Regulatory Issues Manufacturers comply with API performance specifications for manufacturing and using lubricating oils. The EPA — during the process of vehicle certification — ensures fairness in fuel economy testing, factory fill, and other aspects of lubricant usage (U.S. EPA 2010e). Used motor oil is hazardous because of its metal contents and the presence of other compounds. Regulations and enforcement are in place for disposing and recycling of waste oil in the United States. Some states have shown interest in regulating aftermarket oils to help consumers avoid obsolete and poor quality oils.

CHAPTER 6. SUMMARY AND CONCLUSIONS

Since the mid 1970s, substantial progress has been made in controlling automobile emissions. With the phaseout of leaded gasoline, deployment of the three-way catalyst, electronic ignition systems, and myriad of incremental changes, emissions from gasoline automobiles on the market today are a vast improvement over those of earlier times. Whereas progress on reducing emissions from diesel-powered vehicles has until recently been at a slower pace, with the introduction of low-sulfur fuel and improved control technologies, emissions from current engines are clean compared even with 2004 engines. However, despite significant progress, many questions remain unanswered about human exposure to air pollution and the health effects of such exposures.

The context in which automobiles function today has become far more complex, especially in view of the mobility and transportation needs of an increasing global population. Given concerns about climate change, efficiency, and energy security, there is an imperative to find new solutions to enable mobility while overcoming problems related to climate, energy security, and cost, along with air pollution. This complex situation provides the impetus for rapid development and introduction of a broad range of new fuels, technologies, and sources of energy to meet the needs of the transportation sector.

The ultimate development and penetration of new fuels and technologies will, of course, depend on a variety of factors beyond technical feasibility, including:

- Relative cost of the new feedstock or technology compared with the alternative
- The value of the new fuel or technology relative to the one it is replacing, including the willingness of the consumer to pay for a higher-cost product
- Alternative use of the proposed new materials or feedstock (in the case of fuels)
- Taxes, incentives, and mandates

Within this larger context, HEI was founded to provide timely information and analyses on the health effects from mobile sources. To gather an authoritative outlook on the short-term future of emerging technologies and fuels to inform HEI's research, the HEI Board of Directors established SCET, a multidisciplinary team of engineers, fuel experts, regulators, and other experts to help obtain a better understanding of the state of the field and explore new developments that are likely to play a significant role within the next 10 to 15 years. The Committee, chaired by Christine Vujovich and Alan Lloyd, with 16 other members, surveyed and evaluated new fuels and technologies, the likely time frame of their application, emissions of potential concern and key issues that need further attention and research. The results of the Committee's comprehensive deliberations are presented in this report.

It is very likely that our near-term future will be a multi-fuel future. Rather than relying as extensively on oil as the source of energy to power vehicles — most of it imported to the United States and Europe from other countries — we will use increasing amounts of ethanol and other potentially renewable fuels as well as electricity. Developing fuels that are truly carbon-neutral is not yet within reach, but progress is being made. On the technology front, there is much continued interest in further reducing traditional emissions as well as reducing GHG emissions, improving fuel efficiency, thereby helping reduce the carbon footprint from the transportation sector. Also, as we begin to reduce dependence on oil as the chief energy source, the century-old domination of the conventional internal combustion engine is also expected to change substantially. Although the internal combustion engine will endure through the next 10 to 15 years, it will be supplemented, and in some cases superseded, by the electric powertrain.

Finally, in its deliberations, the Committee focused largely on developments and trends in the United States and, to a limited extent, Europe and other developed markets. However, other regions of the world, especially the rapidly developing countries of China and India, are increasingly important customers for automobiles; their markets are growing faster than those of the developed countries. Whereas there are expected to be some similarities in the emergence of new fuels and technologies in the developing and in the developed world, there will also be many differences in the nature, pace of introduction, and impact of these materials. To keep this report within bounds, we only touched on issues that relate to developing nations, although the Committee remains interested in this important topic and may address it in future assessments.

To address the emerging fuels and technologies discussed in this report, SCET reviewed the full range of potential changes, focused on those that are most likely to come to market in the next decade, and identified those that might pose important questions of unintended health consequences as they are developed and deployed. On the basis of the detailed review conducted by SCET and presented in the previous chapters, the Committee identified the following as key issues going forward.

INTERNAL COMBUSTION ENGINE TECHNOLOGIES

The technology chapter takes a careful look at new developments in technologies for both gasoline- and diesel-powered vehicles. In the context of accelerated progress, the Committee notes several key areas that need further consideration and investigation by HEI and others in the scientific community. A summary of the Committee's evaluation is presented in Table 4.

Gasoline Direct-Injection Technology

GDI technology is well established and expected to spread broadly within the gasoline engine market in the near term. Coupled with engine downsizing and turbocharging, GDI will give a significant boost to fuel economy and the concomitant reduction in carbon dioxide emissions. The major concern related to the use of GDI is higher emissions of PM, both mass and UFP emissions, although these emissions are likely less than those from lean-burn engines. These emissions have not been well characterized and their potential health effects are not well understood. There are also some indications of regulatory actions in California to reduce the mass and the number of PM from these engines under its LEV III standards, and actions in Europe that could affect the emissions of UFPs.

Selective Catalyst Reduction

SCR systems are being introduced to control the emissions of NO_x from diesel engines. The introduction of urea as the reducing agent gives rise to concerns regarding the formation of nitrogen-containing compounds, including nitro-PAHs, in emissions and possibly other toxic compounds. Thus, even though the combination of DPF and SCR will substantially reduce criteria pollutants and unregulated pollutants, conclusions regarding the overall risk from air toxics are difficult to draw at this point because such exhaust has not been characterized in detail. The Committee noted that the second phase of the HEI ACES study will characterize exhaust from heavy-duty engines equipped with DPF and de-NO_x exhaust aftertreatment systems (model year 2010).

ELECTRIC DRIVE TECHNOLOGY

Engine electrification is likely to significantly expand within this decade, initially in the form of hybrids, with the potential of moving to all EVs, and ultimately to FCVs. Although tailpipe emissions from such cars are reduced (as in the case of hybrids) or eliminated (in the case of BEVs and FCVs), the Committee identified other issues that need attention. A potentially important issue is whether there are health effects associated with exposures to electric and magnetic fields during operation of these vehicles. Another issue relates to the use of highly reactive metals — especially lithium — and possibly flammable electrolytes in the battery and the potential for human exposure to lithium during the entire life-cycle (from mining to recycling and disposal) or in the event of automobile accidents. Finally, there is the issue of increased emissions associated with electricity generation to charge EVs. In the near term, a large proportion of electricity in specific regions of the United States will continue to be produced by coal-fired power plants, potentially increasing emissions and exposure to some populations; there are also concerns about increased GHG emissions from such plants. If electricity is generated from renewable sources, the emissions profile will be different, and likely of less concern. There are little or no empirical data available on these issues, and they need further research and investigation.

Table 4. Summary of Emerging Technologies and Associated Issues

	Pollutant(s) of Concern	Research Priority[a]	Rationale for Priority Assigned
Engines			
Gasoline direct injection–stoichiometric	PM mass, UFPs	H	Universal use
Gasoline direct injection–lean burn	PM mass, UFPs	M	Uncertain use
Turbocharging (gasoline)	None	L	No issues
High-efficiency dilute gasoline engine	PM mass, UFPs, HCs, aldehydes[b]	M	Moderate use likely; little data available
Homogeneous charge compression ignition	HCs, aldehydes, CO, PM[c]	L	Use not imminent
Low temperature diesel combustion	HCs, aldehydes, CO	L	Control of pollutants readily accomplished
Exhaust Aftertreatment			
Diesel particulate filters–active and passive	NO_2, UFPs, nitro-PAHs, sulfates,[d] metallic UFPs[e]	L	Relatively clean; generally used with selective catalytic reduction in modern engines
Retrofit diesel particulate filters	NO_2, UFPs, sulfates,[d] probable nitro-PAHs	M	Same concerns as for filters used in new equipment, but much less data available
Retrofit diesel oxidization catalyst	NO_2, PM, sulfates,[d] probable nitro-PAHs	L	Not widely used
Selective catalytic reduction using urea	N-containing compounds, dioxin[f]	H	Advanced Collaborative Emissions Study collecting data
NO_x adsorber	N_2O, H_2S, and other possible by-products	L	Less use than selective catalytic reduction; less data; control of emissions readily accomplished
Electric Drive Technologies			
Hybrid electric vehicles	Electromagnetic fields, lithium, and emissions from power plants	M	Little data; increasing use of hybrid electric vehicles likely in near term; large-scale use of all electric vehicles possible in 10+ years
Plug-in and battery electric vehicles			
Fuel-cell vehicle (hydrogen)			
Other			
Brake wear	PM, metals, asbestos in some circumstances	L	Regulatory efforts in place at state levels to manage composition
Tire wear	PM, metals, PAHs	M	Emissions greater than for brake wear; has received less attention so far
Lubricating oil	PM, metals	M	Largely unstudied area; may affect emissions directly and indirectly

[a] Letters denote the Committee's conclusions on research priority levels: H denotes high, M medium, and L low.

[b] HC and aldehyde emissions may be of concern with highly dilute stoichiometric engines.

[c] PM emissions are an issue if stratified combustion is used.

[d] Sulfate is produced from any sulfur in fuel or lubricating oil.

[e] Metallic UFP emissions are a concern when metal-fuel additives are used.

[f] Dioxin emissions may be an issue if copper is used as a catalyst in selective catalytic reduction.

Table 5. Likelihood of New or Increased Use of Transportation Fuels in the Next Decade[a]

	Feedstocks						
Fuel	Petroleum	Natural Gas	Coal	Biomass (Food Crops)	Biomass (Cellulosic and Other)	Oil Sands[b]	Oil Shale[c]
Gasoline	Current	L	L	—	L	Current	M
Ethanol, in gasoline blends	L	L	L	Current	L/M	L	L
Ether, in gasoline blends	L	L	L	L[d]	L	L	L
Diesel[e]	Current	H[f]	L/M	L	L/M	Current	M
Biodiesel, in diesel blends	—	—	—	H	L	—	—
Dimethyl ether[g]	—	L	L	—	L	—	—
LPG[h]	Current	Current	L	L	L	L	L
CNG	L	Current	L	L	—	L	L
Methanol[i]	L	M	M	L	L/M	L	L
Electricity[j]	—	H	H	—	L/M	M	L
Hydrogen[k]	L/M	M	L/M	—	L	L	L

[a] Likelihood represents the probability that the use of a fuel will grow to more than about 0.5% of total fuel supply; it is expressed as low (L), medium (M), or high (H).

[b] Fuel from oil sands may be associated with high GHG emissions.

[c] Fuel from oil shale may be associated with high GHG emissions.

[d] Significant amounts of ethyl *tertiary*-butyl ether are made from ethanol, especially in France.

[e] Likelihoods shown in this row are for hydrocarbon diesels made from a variety of feedstocks.

[f] Diesel fuel can be made from natural gas through the Fischer-Tropsch process.

[g] Increases in the use of dimethyl ether, if any, will most likely be outside the United States.

[h] LPG is generally separated from petroleum and natural gas. Volumes are constrained by the use of both fuels. As natural gas use increases, the availability of LPG will likely increase as well.

[i] Methanol use may increase in developing countries, but probably not in the United States, Europe, and Japan.

[j] Electricity will also be produced in increasing volumes from nuclear, solar, and wind power.

[k] Likelihoods shown in this row are for hydrogen use in fuel-cell vehicles. Hydrogen may also be produced by electrolysis of water using electricity. Hydrogen may be used as a fuel for internal combustion engines, but this use is considered of low likelihood.

FUELS FOR INTERNAL COMBUSTION ENGINES

Consistent with other parts of this report, the fuels chapter evaluates the outlook for fuels over the next 10 years. Changes in fuel composition, demand, and use patterns are considered for the United States, as well as for other regions of the world. While there are many common directions, there are also areas where we expect to see national and regional differences. As in the case of technologies, the Committee emphasizes that the exact fuel mix used for transportation will depend on many other factors, beyond the technological possibilities. The major themes the Committee deemed to be significant are described in the sections that follow. In addition, Table 5 summarizes the outlook, or likelihood of use, for all significant fuels, some of which warrant further consideration and investigations by HEI and by others in the scientific community.

Use of Ethanol in Gasoline Will Increase

In response to national and regional legislative mandates in the United States and Europe, the use of ethanol as fuel is very likely to increase substantially in the United States from 10 billion GPY in 2009 to potentially 36 billion GPY by 2022. Ethanol is widely used currently and blended with gasoline, typically at 10%. With specifically designed engines, nearly neat (85%) ethanol can also be used. Emissions from the use of fuels containing more than 10% ethanol—including the impact of blending, driving cycles, exact engine and emissions-control technology—are not well understood. However, it is expected that the use of ethanol will lead to increased emissions of acetaldehyde and ethanol itself, and to reduced emissions of hydrocarbons, CO and benzene. More research is needed on the emissions and operability effects of ethanol blends in on-road and nonroad applications. The outlook for other alcohols and oxygenates is less certain at this point.

Use of Fatty Acid Esters in Diesel Fuel (Biodiesel) Will Increase

There is a great deal of interest in the use of fatty acid esters in diesel fuel. Although information on emissions is limited, there is concern that the use of biodiesel will possibly lead to increase in emissions of NO_x and aldehydes while reducing emissions of hydrocarbons, CO, and PM. More research is needed on the impact of biodiesel on the emissions and operability of engines equipped with new technologies.

Environmental Issues Related to the Source of Fuels Will Be Important

In addition to the use of alcohols, governments and private companies have given priority to finding new sources of fossil fuels. Several such sources have been identified and are being developed with increasing intensity. Introduction of fuels made from nonpetroleum fossil sources — such as coal, shale, and tar sands — may cause changes in the emissions characteristics of the fuel ultimately produced. Emissions and other effects on the environment associated with the production of these fuels are potentially serious and need to be more fully understood. Some of these impacts are best understood through the use of LCA, so that the effect of tailpipe emissions as well as emissions or any secondary effects from the source of power to the ultimate disposal of materials may be taken into account.

Use of Metallic Additives in Fuels Is a Continuing Concern

Phaseout of lead is one of the most notable developments of the last quarter of the twentieth century; it is expected that lead will be eliminated from the gasoline used in all countries in the near term. However, the use of metal additives as octane boosters or for other purposes continues to be an area that deserves scrutiny. Although fuel suppliers in the United States do not appear to be inclined toward metal additives, metallic fuel additives are being used in Europe and their use is being considered in some developing countries. Use of manganese in gasoline and diesel is also continuing in some developing countries. The use of metallic fuel additives is of concern because of the emissions — and possible health effects — of metallic nanoparticles; such emissions may also adversely affect aftertreatment systems.

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ABBREVIATIONS AND OTHER TERMS

ACES	Advanced Collaborative Emissions Study
API	American Petroleum Institute
BEV	battery-powered electric vehicle
CCRT	catalytic continuously regenerating technology
CCS	carbon capture and storage
CNG	compressed natural gas
CO	carbon monoxide
CO_2	carbon dioxide
CRT	continuously regenerating trap
DME	dimethyl ether
DOC	diesel oxidation catalyst
DPF	diesel-exhaust particle filter

EGR	exhaust gas recirculation
EISA	Energy Independence and Security Act
EU	European Union
EVs	electric vehicles
FCVs	fuel-cell vehicles
F-T	Fischer-Tropsch
g/bhp-hr	grams per brake horsepower-hour
GDI	gasoline direct-injection
GHG	greenhouse gas
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation
GPY	gallons per year
H_2	hydrogen
H_2S	hydrogen sulfide
HC	hydrocarbon
HCCI	homogeneous charge compression ignition
HDD	heavy-duty diesel
HCN	hydrogen cyanide
HEDGE	high-efficiency dilute gasoline engine
HEVs	hybrid electric vehicles
LCA	life-cycle analysis
LDVs	light duty vehicles
LEV III	Low-Emission Vehicle III standards
LNG	liquefied natural gas
LPG	liquefied petroleum gas
MeOH	methanol
MMT	methylcyclopentadienyl manganese tricarbonyl
MTBE	methyl *tertiary*-butyl ether
N_2O	nitrous oxide
NAC	NO_x adsorber catalyst
NH_3	ammonia
NRC	National Research Council
NO	nitric oxide
NO_2	nitrogen dioxide
NO_x	oxides of nitrogen
PAHs	polycyclic aromatic hydrocarbons
PHEVs	plug-in hybrid electric vehicles
PM	particulate matter
PMP	Europe's Particulate Measurement Programme
ppm	parts per million
RFS	Renewable Fuels Standard
SAE	Society of Automotive Engineers
SCET	Special Committee on Emerging Technologies
SCR	selective catalytic reduction
SO_2	sulfur dioxide
SO_x	sulfur oxides
U.S. DOE	U.S. Department of Energy
U.S. EPA	U.S. Environmental Protection Agency
UFPs	ultrafine particles

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