Diesel Passenger Vehicles and the Environment

Diesel cars and light trucks are receiving heightened attention as a near-term strategy to meet fuel economy and climate change goals. But amidst growing interest in diesels for passenger vehicles, there is also concern over the public health implications of expanding diesel’s market share.

While pollution from diesel passenger vehicles has been cut by a factor of 5–10 over the past two decades, it must be reduced another factor of 10 within the next few years in order to meet near-term pollution standards. Significant emission reductions appear technologically possible, but the engineering, economic, and infrastructure challenges are large. The ten-fold reductions needed to meet next-generation standards will require a very high degree of technical success.

In addition to conventional pollution reductions, diesel engine research must also address evolving public health concerns, including emissions of ultrafine particles and toxics. These emerging issues must be dealt with if diesel is to meet increasingly stringent environmental needs.

An extremely rapid introduction of diesel passenger vehicles could yield carbon emission savings within the decade of up to 4 percent versus the base case. Such reductions could provide headway in the struggle against global warming, but are far from enough. Furthermore, these potential benefits must be appropriately balanced against the air quality risks posed by diesel.

Diesel engines power most of the nation’s trucks, buses, trains, ships, and offroad machinery. Roughly one-fifth of the US transportation sector’s energy is consumed in these engines (Davis 1998), and diesel fuel use is currently growing faster than gasoline consumption (DeCicco and Mark 1998).

Diesel Passenger Vehicle Markets

Diesel passenger vehicles comprise a small share of the US fleet, accounting for approximately two percent of the fuel consumed by cars and light trucks today (Davis 1998). Currently, diesel cars make up a modest 0.1 percent of automobile sales, while diesel has now captured roughly 4 percent of light truck sales¹ (Davis 1998; AAMA 1996).

US Trends. US diesel automobile sales peaked during the early 1980s in the wake of two major oil shocks (Figure 1). Forecasts at that time projected sales would reach 20 percent by 1990 (DOT 1991). But fluctuations in the price of diesel fuel, declining gasoline prices, and vehicle performance problems all led to the diesel auto’s decline in the United States (Sperling 1988; Cronk 1995).

Diesel light truck sales also experienced a boom in the early 1980s, although recent increases have far surpassed previous sales as the entire light truck market has grown quickly. US factory sales² of diesel light trucks have more than doubled in the past five years.

¹ Vehicles up to 10,000 pounds gross vehicle weight (GVW). Traditionally, light trucks have been categorized as vehicles up to 10,000 pounds GVW; however, air quality regulations define light trucks as vehicles up to 8,500 pounds GVW.

² Actual sales numbers were not available. Factory sales constitute the majority of, but not all, light trucks sold in the United States.
years, especially in the heavier light truck segment (6,000–10,000 pounds gross vehicle weight) (AAMA 1996). Ford currently makes about 200,000 light trucks per year powered by Navistar diesel engines. Chrysler sells 60,000 Dodge Ram pickup trucks annually with Cummins diesel engines and may soon build sport-utility vehicles with Detroit Diesel engines. GM has recently announced plans to ramp up production of diesel engines for large light trucks with Isuzu (Nauss 1998; Konrad 1998).

For diesel engine manufacturers, the light truck market is an opportunity for companies that currently sell hundreds of thousands of engines to begin producing millions of engines. At present, most of these engines are scaled-down versions of larger units built for heavy trucks. But most engine makers are pursuing even smaller engines that could be introduced more broadly throughout the market (Cummins 1998).

**CAFE Shortfalls.** Automakers’ renewed interest in diesel engines for the US market has been spurred in large part by fuel economy regulations—the Corporate Average Fuel Economy (CAFE) standards. Despite the fact that light trucks are held to a lower standard than automobiles, domestic automakers are falling short of their truck CAFE requirements (Eisenstein 1997). These shortfalls are largely due to record sales of the most profitable but least efficient vehicles, particularly sport-utility vehicles and heavy pickups. If light truck fuel economy does not improve in the coming years, domestic auto makers will be unable to accrue credits to offset the substantial debits that have accumulated during the past 2–5 years (Figure 2). By delivering a fuel economy improvement of up to 30–50 percent, diesel engines are an attractive strategy for complying with the standards.

**International Growth.** Overseas markets for diesel passenger vehicles have historically been much larger than in the United States. Many countries in Europe and parts of Asia levy significantly higher taxes on motor fuels, particularly gasoline, that have spawned consumer interest in higher-efficiency diesel cars. Recent trends in Europe have been towards increasing diesel sales, where roughly one-quarter of all new automobiles are currently diesel powered (Walsh 1998).
Diesel Passenger Vehicles and the Environment (1997, Krieger et al. 1997). France, where roughly half of all new sales are diesel, has a particularly high proportion of diesel cars in its fleet (Wang et al. 1997). The trend does not appear to be restricted to Europe, however. In Japan, the number of diesel passenger vehicles appears to have tripled in the past decade (based on Walsh 1997).

As a result of increasing globalization, most automakers selling in the US market now also produce diesels for international markets, some on their own and some with foreign partners. This permits many companies to transfer research, development, and even production experience among global divisions. Traditionally, the tighter US air quality standards have made the transfer of diesel technology to North America difficult without additional development costs. But the worldwide trend towards tighter emission standards is forcing technology improvements that may put more diesels in reach of the US standards. Conversely, research aimed at meeting the US targets will eventually pay off in foreign markets.

**Climate Change.** The renewed interest in diesels is also driven by growing attention to climate change as a major environmental concern. The higher efficiency of diesel vehicles results in lower emissions of carbon dioxide, the chief gas responsible for global warming. While automakers officially opposed the recent Kyoto Protocol that established legally-binding cuts in greenhouse gas emissions, many have demonstrated high-efficiency prototypes powered by diesel as climate change mitigation technologies.5

**Federal Support.** Over the past five years, the US federal government’s interest in diesel vehicles has increased considerably, with consequent increases in research funding. Many federal agencies are sponsoring research on diesel vehicles, but the majority of research for passenger vehicles is funded by the Department of Energy, whose diesel budgets have been on the rise in recent years (Figure 3).

Federal interest in diesels stems largely from the Administration’s focus on global warming and energy security as environmental policy priorities. Diesel is a priority component of the joint government-industry research project, the Partnership for a New Generation of Vehicles (PNGV). Launched in 1993, PNGV’s primary goal is to develop a production-ready prototype of an 80 mile-per-gallon automobile by 2004. While several promising technologies are under consideration by PNGV, the lead option is a hybrid vehicle powered by a diesel engine.

In addition to funding research on diesel passenger cars under PNGV, the federal government is also engaged in research to assist diesel engines in capturing a larger share of the light truck market. Under

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5 For example, a recent Toyota advertisement in *Time* magazine reads: “If You’re Concerned About Global Warming You Should Be Interested in Diesel Engines.”
a Light Truck Clean Diesel (LTCD) program, the Department of Energy is working with industry to develop cleaner light-duty diesel engines.

**Diesel Engines and Global Warming**

A vehicle using a state-of-the-art diesel engine, the so-called compression ignition direction injection (CIDI) engine (see Box 1), offers a substantial fuel economy gain over today’s gasoline engines. However, a portion of the higher fuel economy is a result of diesel fuel’s higher density: each gallon of diesel contains roughly 11 percent more energy. Correcting for fuel density, today’s best diesel cars are over 45 percent more efficient than their counterparts. This higher efficiency translates directly into 30–35 percent savings of carbon emissions, the chief gas responsible for global warming (Table 1).

**Diesel Fuels.** Future diesel fuel may need to be modified or replaced with alternatives to assist diesel engines in meeting air quality goals. Compared to conventional diesel, some of these fuel changes will yield higher greenhouse gas emissions. For example, Fischer-Tropsch diesel, a fuel manufactured from natural gas feedstocks, has the potential to lower emissions of key air pollutants but would increase carbon emissions by over 20 percent compared to conventional diesel (Figure 4). In contrast, compared to gasoline vehicles, this would reduce diesel’s carbon benefits to 15–20 percent, rather than the 30–35 percent achievable with the best diesel engines available today.

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**BOX 1**

**Diesel Technology Basics**

State-of-the-art diesel passenger vehicles are powered by compression ignition direction injection (CIDI) engines.

**Compression Ignition (CI) vs. Spark Ignition (SI).** Traditional gasoline vehicles are powered by spark ignition (SI) engines, which use a spark to initiate combustion. In the compression ignition (CI) engines used in diesel vehicles, the fuel and air mixture spontaneously ignites as it is compressed in the engine’s cylinders. CI engines are more efficient during ideal conditions because they operate at higher compression ratios, permitting them to get more useful work out of each cycle. Diesel combustion can also be designed to occur away from the cylinder walls, reducing heat loss. As a result, the peak thermal efficiency of CI engines can be typically 10–30 percent higher than for SI engines. Diesel engines are also more efficient under real-world driving conditions, when a vehicle’s power demand fluctuates extensively. SI engines restrict the flow of the fuel and air mixture entering the cylinders when full power is not required, creating additional “throttling” losses and pumping losses. In contrast, CI engines reduce only the fuel supplied in order to lower power output. Accounting for these additional driving cycle benefits, diesel engines can be a total of 25–50 percent more efficient than gasoline engines (Arcoumanis and Schindler 1997).

**Direct Injection (DI) vs. Indirect Injection (IDI).** Most heavy vehicles today use direct injection (DI) diesel engines, while until recently most automobile-size diesel engines have used indirect injection (IDI) technology. DI engines inject fuel and air directly into the cylinder, while an IDI engine uses a prechamber to help mix the fuel and air before entering the main cylinder. The IDI system comes with a 15 percent efficiency penalty compared to the DI because the prechamber permits additional energy losses (Ashley 1997; Arcoumainis and Schindler 1997), but its superior fuel and air mixing has been essential for diesel passenger vehicles. The small, high-speed engines used in automobiles require fuel and air to mix 10 times faster than in larger engines (Heywood 1988), something that has been difficult to achieve without a prechamber. Only recently have diesel engine developers overcome this mixing limitation with DI engines.
biodiesel fuels manufactured from agricultural feedstocks would reduce carbon emissions by three-fourths.

**Potential Carbon Savings.** The widespread introduction of higher-efficiency diesel engines into the US passenger vehicle market has the potential to deliver important carbon savings. In the absence of higher fuel economy standards or a major fuel price increase, however, per-vehicle efficiency gains do not yield fleetwide fuel economy benefits *per se*. Over the past decade, engine and drivetrain efficiency improvements have translated into performance and weight gains rather than actual on-road fuel efficiency improvements.\(^8\)

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\(^8\) For example, passenger car weight has increased 8 percent on average over the past decade while 0–60 acceleration time has improved 19 percent and fuel economy has remained stagnant. Light truck weight has increased 15 percent on average while acceleration has improved 17 percent. (Heavenrich and Hellman 1996).

Assuming that increasing diesel sales yield actual on-road fuel efficiency gains, the total fleetwide carbon savings are limited by several additional factors: (a) the speed of market entry, (b) the efficiency penalty associated with engine modifications or aftertreatment devices needed to meet air quality targets, and (c) the carbon content of the diesel fuel used. Figure 5 illustrates one potential pathway for dieselization, in which diesel passenger vehicle sales increase from 3 percent in 2001 to 50 percent by 2010 (and constant thereafter). This represents an extremely aggressive scenario, in which diesel would overtake the passenger vehicle market more than two times faster than occurred in France, which has one of the most heavily dieselized car markets.\(^9\)

If conventional diesel is used in this new diesel fleet, passenger vehicle carbon emissions would be 4 percent lower than in the base case by 2010 and

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\(^9\) France’s fuel prices are also 2.4 to 3 times higher than those in the United States (Davis 1998).
Diesel Passenger Vehicles and the Environment

If a cleaner diesel is required, such as Fischer-Tropsch diesel, carbon benefits may be substantially attenuated (Figure 6). Passenger vehicle carbon emissions must be reduced by over 30 percent in 2010 to return to pre-1990 levels and meet the targets established in the Kyoto Protocol. Thus, additional measures and alternative pathways will be required for the transportation sector (UCS 1998).

**Diesel Engines and Air Pollution**

As with fuel use, heavy vehicles and nonroad equipment account for the majority of existing diesel pollution, rather than the relatively few diesel-powered passenger vehicles on the road today. If diesel engines were to capture a large share of the car and light truck market, however, the impact of diesel engines could increase. Critically important is how the environmental performance of diesel passenger vehicles would compare with that of the displaced gasoline vehicles.

**Health Effects.** Collectively, diesel-powered vehicles account for nearly three-quarters of all direct particulates (PM) from US transportation and over half of all nitrogen oxides (NOx)—a precursor to both smog and fine particles (EPA 1998a). In urban centers, where exposure to diesel exhaust may be especially high, diesel engines can be a dominant source of particulates (Walsh 1997). Furthermore, diesel exhaust is increasingly being scrutinized as a potential human carcinogen.

Diesel vehicles offer clear benefits for one key pollutant, carbon monoxide (CO). Although problems persist in some urban regions, roughly three times more US citizens live in areas not currently meeting the federal ozone standards than in areas not attaining CO standards (EPA 1999). Thus, while CO continues to be an important motor vehicle pollutant, this analysis focuses on the more significant hazards of urban ozone, particulates, and toxics.

**Urban Ozone.** NOx and hydrocarbon emissions from motor vehicles contribute to ozone (smog), the major ingredient in the smog engulfing major cities. High up in the stratosphere, ozone shields us from harmful ultraviolet (UV) rays. Yet at ground level, ozone irritates the respiratory system, causing

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10 The NOx estimates from diesel highway vehicles is likely to increase as new information regarding high emissions during highway operation (Walsh 1998) is incorporated into official inventories. In addition, new information about high PM emissions from malfunctioning gasoline vehicles (Cadle et al. 1998) may affect future estimates of PM inventories.
coughing, choking, and reduced lung capacity. Urban ozone pollution has been linked to increased hospital admissions for respiratory problems such as asthma and daily mortality, even at levels below the current standard (ATS 1996). Some early studies suggest that long-term exposure to ozone may yield chronic, irreversible impacts on lung function (Tashkin et al. 1994). More recent work has tended to support this conclusion in preliminary studies (Kunzli et al. 1997).

**Particulates.** Motor vehicles create particulate matter pollution by emitting combustion particles directly to the air and by releasing pollutants, notably NOx and hydrocarbons, that form secondary particles in the atmosphere. Particulates irritate the eyes and nose and aggravate respiratory problems. Children, the elderly, people with pre-existing heart or lung disease, and asthmatics are particularly at risk from exposure to particulates (EPA 1997a).

Fine particulates, those less than 2.5 microns in diameter (PM$_{2.5}$), have also been directly associated with an increased risk of premature death (EPA 1996a; ATS 1996). In one recent study, researchers followed more than 8,000 people in six different locations for 17 years. They found that the risk of premature death in areas with high levels of fine particles was 26 percent greater than in areas with lower levels (Dockery et al. 1993). Based on extrapolations from a larger study of premature mortality and particulates, EPA estimates that its new health standards for PM$_{2.5}$ will save 15,000 lives each year (EPA 1997a).

At present, the specific mechanism by which fine particulates increases mortality risk is unknown (EPA 1996a). As a result, while regulations are based on the total mass of particulates less than 10 or 2.5 microns (see Table 2), other characteristics such as particle size, surface area, number, chemical composition, or physical shape might also be important (Sawyer and Costantini 1997). As a result, control strategies focused solely on reducing the mass of particulates may not proportionally reduce public health risks. In fact, emerging evidence indicates that historic efforts to reduce PM$_{10}$ mass from diesel engines have significantly increased the number of ultrafine particles (those less than 0.1 microns) (Bagley et al. 1996; Walsh 1998; HEI 1997). Smaller particles more readily evade the body's physical defenses, penetrating further into the lungs, and are theorized to cause more health damage (EPA 1996b; ATS 1996).

**Carcinogenesis.** In addition to its contribution to mainstream air pollution problems, major public health agencies also consider diesel exhaust a potential human carcinogen (Table 3). While diesel exhaust contains over 40 compounds thought to cause cancer (CalEPA 1998a), most public health studies of diesel exhaust have focused on the aggregate emissions rather than on specific compounds. In its recent ruling, however, the California Air Resources Board voted to list only diesel exhaust particulates as a toxic, rather than whole diesel exhaust, which contains both particulates and vapor-phase emissions (CARB 1998b).

Studies of humans routinely exposed to diesel exhaust indicate a greater risk of lung cancer. For example, occupational health studies of railroad, dock, trucking, and bus garage workers exposed to high levels of diesel exhaust over many years consistently demonstrate a 20–50 percent increase in the risk of lung cancer or mortality (HEI 1995; Bhatia et al. 1998).

Even at the average rates of exposure experienced by most people, diesel exhaust poses a potential cancer risk. Extrapolating from epidemiological studies,
at current exposure levels it is estimated that up to 450 of every million Californians are at risk of contracting lung cancer as a result of lifetime exposure to diesel exhaust, or over 14,000 residents.\textsuperscript{14}

\textbf{Diesel Exhaust vs. Gasoline Exhaust.} Because emissions from motor vehicles continue to improve in response to new standards, it is difficult to develop an absolute picture of diesel vs. gasoline vehicle emissions. In addition to technology improvements, emission measurement techniques continue to evolve, and emerging public health information is pointing researchers to evaluate new exhaust constituents. Using a combination of measured in-use, certification testing, and modeled emissions, however, a snapshot of today’s best gasoline and diesel technology can be constructed.

\textbf{Urban Ozone Precursors}

\textbf{Nitrogen Oxides.} Diesel passenger vehicles recently certified in the United States have achieved NO\textsubscript{x} emissions of 0.6–0.9 g/mi (EPA 1997b, CARB 1997). Many gasoline cars being sold today have NO\textsubscript{x} certification levels less than half the diesel values, and some are certifying at less than one tenth diesel levels (CARB 1997).

While gasoline vehicles may certify to relatively low NO\textsubscript{x} standards, they will typically emit several times those values in the real world as they age. Diesel passenger vehicles have not been studied as extensively, but their emissions are thought to degrade less than gasoline cars because they do not currently use catalytic converters to control emissions (Fairbanks 1997). This conclusion may change if exhaust control technologies are installed on diesel vehicles in the future.

Emissions modeling suggests that lifetime average NO\textsubscript{x} emissions from diesel vehicles are roughly twice that of gasoline cars being sold in some states by 1999 and the rest of the country by 2001 (Table 4). These results must be viewed with caution, however, because the EPA model used to construct these estimates is based on relatively little diesel vehicle emissions data.

\textbf{Hydrocarbons.} Hydrocarbons are the other key precursor to urban ozone. During the early 1990s, vehicle regulations focused aggressively on lowering hydrocarbon emissions as the chief ozone-reduction strategy. In recent years, the focus of new vehicle regulations aimed at ozone reduction has shifted more to NO\textsubscript{x} reductions.

Nonetheless, diesel cars typically yield lower emissions of hydrocarbons than gasoline vehicles. This is due in large part to the fact that diesel fuel does not evaporate as readily as gasoline. However, hydrocarbon emissions from gasoline vehicles are expected to be cut to near-diesel levels as NLEV vehicles are introduced (Table 4).

<table>
<thead>
<tr>
<th>Organization</th>
<th>Year</th>
<th>Conclusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>National Institute for Occupational Safety and Health</td>
<td>1988</td>
<td>potential occupational carcinogen</td>
</tr>
<tr>
<td>International Agency for Research on Cancer (World Health Org.)</td>
<td>1989</td>
<td>probable human carcinogen</td>
</tr>
<tr>
<td>State of California</td>
<td>1990</td>
<td>known to cause cancer</td>
</tr>
<tr>
<td>US Environmental Protection Agency (Draft)</td>
<td>1998</td>
<td>“highly likely” human carcinogen</td>
</tr>
<tr>
<td>California EPA (Staff Recommendation)</td>
<td>1998</td>
<td>“may cause an increase in the likelihood of cancer”</td>
</tr>
<tr>
<td>California Air Resources Board</td>
<td>1998</td>
<td>diesel particulate emissions are toxic air contaminant</td>
</tr>
</tbody>
</table>

\textsuperscript{14} The independent Scientific Review Panel of the California EPA has proposed a reasonable estimate of cancer risk from diesel exhaust to be 0.0003 for every microgram of diesel exhaust per cubic meter of air (3 x 10\textsuperscript{-4} (µg/m\textsuperscript{3})) (CalEPA 1998b). The current average exposure rate is 1.5 µg/m\textsuperscript{3}, resulting in an average lifetime risk of 4.5 x 10\textsuperscript{-6}.
Particulates

Direct Particulates. Recent data indicates that diesels emit at least 10 and perhaps as much as 300 times more PM mass than properly operating modern gasoline vehicles (Table 5). Many factors—such as vehicle age, condition, temperature, and driving cycle—can impact these vehicle-to-vehicle comparisons. For example, gasoline cars that are malfunctioning can increase PM emissions by a factor of 100. But even emissions from malfunctioning gasoline cars appear to be several times lower than from diesel vehicles.

There may also be key differences in the size distribution of particulates emitted by diesel versus gasoline vehicles, although research has only recently turned to such comparisons. These studies indicate that diesel engines emit larger numbers of smaller particles.\(^15\) For example, Walsh (1998) presents results from a UK study indicating that current indirect injection diesel technology emits nanoparticles and ultrafines at perhaps 100 times the rate of modern gasoline cars over European driving cycles.

More recently, the British oil research consortium CONCAWE tested modern direct injection diesel and conventional gasoline-powered passenger vehicles (Hall et al. 1998). At high speeds, the researchers demonstrated that gasoline vehicles emit roughly the same number of ultrafine particles as the diesels tested and that a higher percentage of gasoline particulates fall into the smaller size ranges. However, their most significant result is that—over the European driving cycles—diesel cars emitted 10–100 times more nanoparticles and ultrafines than modern gasoline vehicles equipped with catalytic converters.

Secondary Particulates. The higher NO\(_x\) emissions of diesel vehicles may yield higher levels of nitrates, an acid aerosol that is an important component

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\(^{15}\) Additional study of this issue is needed, as some concerns about techniques for sampling such small particles persist.
of particulate pollution, especially in the Western United States.$^{16}$

In the case of hydrocarbons, the specific chemical composition of the emissions is likely to be important in determining the contribution of diesel or gasoline exhaust to secondary particle formation. It is currently unclear how important motor vehicle-related hydrocarbons are as a secondary particulate source. Since diesel vehicles emit fewer hydrocarbons than gasoline cars, hydrocarbon-related secondary particulate formation may well be lower.

**Toxics.** Comprehensive and detailed comparisons of the carcinogenic properties of diesel exhaust versus gasoline exhaust have not been made, but early evaluations suggest that important differences may exist. For example, the International Agency for Research on Cancer has classified diesel engine exhaust as “probably carcinogenic” but assigned gasoline exhaust a lower risk of “possibly carcinogenic” (IARC 1989).

More detailed and recent research into gasoline has focused on specific toxic compounds, such as benzene or 1,3 butadiene, rather than whole gasoline exhaust.$^{17}$ Current evidence suggests that diesel exhaust is more potent than these individual toxic constituents (as measured by its unit risk); however, a complete risk assessment would need to compare public exposure to these compounds as well as their potency relative to diesel (Table 6).

**Emission Regulations.** Today’s diesel passenger vehicles are allowed to emit more of two key pollutants, nitrogen oxides (NO$_x$) and particulate matter (PM), than their gasoline counterparts under existing regulations, the Federal “Tier 1” standards (Table 7). This loophole is largest for diesel automobiles and some small pickups and sport-utility vehicles, for which NO$_x$ standards are over two times higher than for gasoline cars. Although gasoline vehicles are not required to meet a PM standard, their emissions are typically 16 times lower than the PM standards for diesel cars.

**National Low Emission Vehicle (NLEV).** Beginning in 1999 in the Northeast and 2001 elsewhere, new standards are coming on line that lower emissions from cars and light trucks up through 6,000 pounds gross vehicle weight (GVW). These standards do not affect heavier light trucks, nor do they eliminate the ability to sell Tier 1 vehicles (for which diesel waivers exist).$^{18}$

**New California Standards (LEV II).** In California, regulators have recently adopted new standards for 2004 and beyond called the Low-Emission Vehicle II (LEV II) program. California’s LEV II establishes tighter standards for all passenger vehicles and removes loopholes that currently (a) permit light trucks to emit more than automobiles and (b) allow diesel vehicles to emit more pollution than gasoline cars. Under LEV II, diesel passenger cars and light trucks up through 8,500 gross vehicle weight (GVW) sold in California must meet the gasoline automobile standards.

**New Federal Standards (Tier 2).** Some states may choose to opt into the California LEV II emissions program. For the remaining states, federal emission standards will apply. “Tier 2” standards are now under development and could come into effect as early as model year 2004. In addition to requiring emission reductions from all passenger vehicles, the

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TABLE 6

<table>
<thead>
<tr>
<th>Compound</th>
<th>Unit Risk$^2$</th>
<th>Range</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>($\mu g/m^3$)$^{-1}$</td>
<td>($\mu g/m^3$)$^{-1}$</td>
</tr>
<tr>
<td>Diesel Exhaust</td>
<td>$3 \times 10^{-4}$</td>
<td>$1.3 \times 10^{-4}$ to $2.4 \times 10^{-3}$</td>
</tr>
<tr>
<td>1,3 Butadiene</td>
<td>$1.7 \times 10^{-4}$</td>
<td>$4.4 \times 10^{-6}$ to $3.6 \times 10^{-4}$</td>
</tr>
<tr>
<td>Benzene</td>
<td>$2.9 \times 10^{-5}$</td>
<td>$7.5 \times 10^{-6}$ to $5.3 \times 10^{-5}$</td>
</tr>
<tr>
<td>Formaldehyde</td>
<td>$6.0 \times 10^{-6}$</td>
<td>$2.5 \times 10^{-6}$ to $3.3 \times 10^{-5}$</td>
</tr>
<tr>
<td>Acetaldehyde</td>
<td>$2.7 \times 10^{-6}$</td>
<td>$9.7 \times 10^{-7}$ to $2.7 \times 10^{-5}$</td>
</tr>
</tbody>
</table>

Source: CalEPA 1998b, p.7 (Appendix II)

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$^{16}$ Nearly 16 percent of PM$_{2.5}$ is thought to be nitrate in the Western U.S. (EPA 1996b). In a more recent study of the Denver metropolitan area, ammonium nitrate accounted for roughly one-quarter of urban area PM and almost half of PM$_{2.5}$ in non-urban regions during the winter (Watson et al. 1998).

$^{17}$ Many of these compounds are also found in diesel exhaust.

$^{18}$ However, sales of vehicles dirtier than the average NLEV requirement (such as diesel Tier 1 vehicles) would have to be offset by cleaner vehicles elsewhere in the fleet.
Tier 2 standards may also close the historic loophole that has permitted diesel vehicles to emit more of some pollutants. As in California, the federal Tier 2 standards could therefore require major reductions in diesel passenger vehicle emissions.

**Research Targets.** While many of these new standards will come on line within the next five years, federal research into both diesel automobiles and light trucks continues to focus on less stringent emission targets. While federal research targets may be subject to change, the current official goals for diesel passenger cars (PNGV) and light trucks (the Light Truck Clean Diesel program) are 3–7 times higher than California’s new emissions standards (Table 7).