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Diesel Exhaust: Health, Environmental, and Economic Effects An Overview

By
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Abstract: The air pollutants contained in today's diesel exhaust are associated with many types of serious health, environmental, and economic effects. Quantitative analysis that covers a portion of these effects shows that, if unchecked, future emissions from diesel vehicles could lead to large numbers of harmful health effects and billions of dollars of environmental and economic damage each year.

The exhaust emissions from diesel engines that power trucks, buses, construction and farm equipment, and many types of nonroad vehicles contain a wide range of air pollutants that are associated with many types of serious health, environmental, and economic effects. The prevalence today of vehicles that rely on diesel fuel contributes to substantial levels of these pollutants in our air. There is increasing concern by EPA and other governmental agencies over the effects that diesel exhaust from today's engines may be having for both highway and nonroad vehicles. This paper identifies the major pollutants contained in diesel exhaust, provides estimates of their emission levels, and discusses the air quality, health, environmental, and economic effects associated with these pollutants.

Pollutants and their Formation

Diesel exhaust is a complex mixture of hundreds of constituents in either a gaseous or particle phase. Many of the compounds in diesel exhaust contribute to major air pollution concerns throughout the United States.(1) The exhaust contains nitrogen dioxide, sulfur dioxide (SO_2), carbon monoxide (CO), and particulate matter particles less than 10 microns in size (PM_{10}) that are covered by the Clean Air Act's National Ambient Air Quality Standards (NAAQS). Sulfates in diesel exhaust are also covered in the PM_{10} standard. Nitrogen dioxide and other oxides of nitrogen (NO_x) and hydrocarbons contained in diesel exhaust contribute (as precursors) to the formation of ozone and fine particles ($PM_{2.5}$), which are other NAAQS pollutants. SO_2 also contributes to fine particle formation. EPA has recently designated "diesel particulate matter and diesel exhaust organic gases" as a Mobile Source Air Toxic (MSAT) under the CAA.(2) Additionally, benzene, formaldehyde, acetaldehyde, 1,3–butadiene, and acrolein are five other MSATs that EPA is focusing on now because they occur at substantial quantities within diesel exhaust and existing data suggests that they may have a greater inhalation risk to the public than many other air toxics contained in diesel exhaust. Very small amounts of dioxins are also formed by and emitted from heavy-duty diesel trucks. Also, polyaromatic hydrocarbons (PAHs) and their derivatives, which laboratory testing suggests may be highly toxic, are also found in diesel exhaust. Many other air toxics (organics and metals) are found in small amounts.(3) There is also the emission of carbon dioxide (CO_2) that results from the diesel combustion process, which is the most prevalent greenhouse gas. Other compounds in diesel exhaust include oxygen, nitrogen, and water vapor.(4)

The combustion of diesel fuel in the engine of a vehicle leads to the formation of pollutants that 1) occur as the product of the combustion process, 2) result from incomplete combustion, 3) pass through the engine "uncombusted," and 4) form either in the exhaust gases, or ambient air.(4) Nitrogen oxides, sulfur dioxide, sulfates, carbon monoxide, and carbon dioxide form through the reaction of fuel and air in the combustion process and are several of its byproducts. Their levels depend critically on the temperature, air feed rates, and efficiency of the combustion process as well as the composition of the fuel

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(e.g. sulfur content). Particulate matter and several toxic organics result as the product of incomplete combustion. Certain air toxics, such as benzene, pass through the engine in small amounts without combustion.

There is secondary formation of pollutants in vehicles' exhaust when various compounds combine together to form fine and ultra fine particles, or gaseous chemical pollutants. There also is secondary formation of pollutants in the atmosphere from the byproducts of the combustion process. Emitted organic compounds can combine to form formaldehyde or acetaldehyde. The nitrogen oxides and sulfur dioxide can in the presence of ammonia transform in the atmosphere into fine particle nitrates and sulfates. The nitrogen oxides and organic hydrocarbons combine in the presence of heat and sunlight to form ozone primarily in the summer months.

Air Emissions

EPA has estimates of current direct emissions of major air pollutants from diesel-powered vehicles and forecasted future emission levels.(5,6,7,8,9) Table 1 shows these results for 1996 and 2007. The table also provides estimates of the contribution of diesel-powered vehicles to the total emissions inventory of all sources. The "selected major air toxics" group covers benzene, acetaldehyde, formaldehyde, 1,3-butadiene, and acrolein. For both PM_{10} and $PM_{2.5}$ emissions, the estimates exclude emissions from natural and miscellaneous sources. Notably, the table shows that diesel engines have been and will be a substantial contributor of NO_x, particulate emissions and the air toxics covered. These engines are a modest contributor of many other pollutants. Diesel engines emit about a quarter of all NO_x emissions in 1996 and 2007. Diesel engines emit around 15 percent and 10 percent of the PM_{10} emissions during these years. For $PM_{2.5}$, diesel engines provide about 20 percent and 15 percent of the emissions in 1996 and 2007, respectively. For the selected major air toxics, all diesel mobile sources are close to 20 percent of the total emissions in 1996.

Air Quality

EPA typically considers the nation's air quality from the standpoint of attainment of different areas of the country with the NAAQS. In July 2000, there were 31, 14, 28, and 17 areas in "nonattainment" with the existing one-hour ozone, PM_{10}, SO_2 and CO standards, respectively.(1) Table 1 shows that diesel exhaust is a substantial component of annual NO_x emissions contributing to ozone nonattaiment and to PM_{10} emissions. In the recent 2007 Heavy-Duty Engine (HDE) rule covering diesel trucks and buses, EPA examined the outlook for future attainment with the one-hour ozone standard and PM_{10} standard. The analysis showed that 45 metropolitan areas that had a 1999 population of 128 million people had a risk of exceeding the one-hour ozone standard between 2007 and 2030.(1) Notably, EPA's air quality modeling suggested that even the large reductions in NO_x from lowering emissions by over 90 percent in new diesel trucks, left most areas with future exceedences of the ozone standard through 2030.(10) EPA's analysis also showed that about 10 areas that had a 1999 population of 28 million people had a significant risk of exceeding the PM_{10} standard between 2007 and 2030. Figure 1 shows the areas that EPA forecasts are at risk of not attaining the ozone and PM_{10} standards. Looking ahead at implementation of the fine particle standard, EPA's modeling analysis of the recent diesel rule indicated that without additional regulatory actions two-thirds of the U.S. population will live in areas of the country with fine particle levels exceeding the fine particle standard by 2030.(1)

Table 1
Air Emissions from Highway and Nonroad Diesel Engines,
All Mobile Sources, and All Sources for 1996 and 2007
without Inclusion of the 2007 HDE Rule[a]
(Thousand short tons)

Pollutant/Sources	**Highway Diesel**	**Nonroad Diesel**	**All Diesel**	**All Mobile Sources**	**All Sources**
	1996				
Nitrogen Oxides	4,335	2,723	7,058	14,512	26,117
Sulfur Dioxide	74	453	527	1,143	18,789
PM_{10} (excluding natural and miscellaneous emissions)[b]	190	271	461	750	2,931
$PM_{2.5}$ (excluding natural and miscellaneous emissions)[b]	167	249	417	640	2,124
Carbon Monoxide	1,400	1,376	2,776	78,113	98,637
Hydrocarbons	225	408	633	8,135	18,522
Selected Major Air Toxics[c]	45	114	159	567	869
Carbon Dioxide (MMTCE)[d]	80	35	115	491	1,463
	2007				
Nitrogen Oxides	2,644	2,247	4,892	10,677	20,566
Sulfur Dioxide	92	675	767	1,160	17,105
PM_{10} (excluding natural and miscellaneous emissions)[b]	109	209	319	609	2,817
$PM_{2.5}$ (excluding natural and miscellaneous emissions)[b]	92	192	284	502	1,936
Carbon Monoxide	964	1,121	2,085	70,357	92,941
Hydrocarbons	185	229	414	5,118	14,259
Selected Major Air Toxics[c]	34	73	107	328	Not available
Carbon Dioxide (MMTCE)[d]	112	41	153	619	1,738

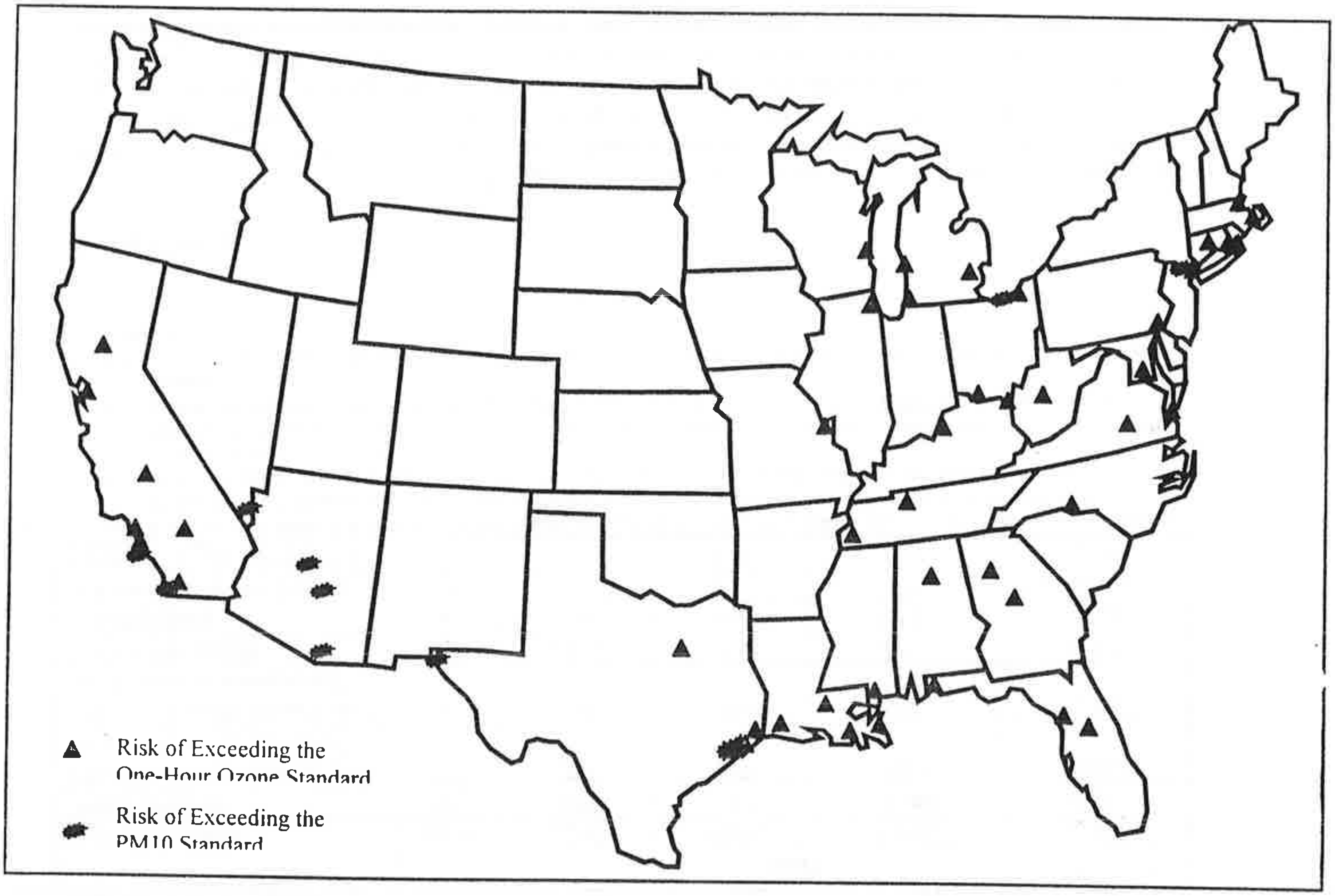
a. For 2007, this table is an forecast without implementation of the 2007 Heavy-Duty Engine rule which begins a phase-in of highway fuel changes to lower sulfur content and lowering of emissions standards for new heavy-duty trucks.
b. These particulate emission estimates exclude natural (geogenic) sources and miscellaneous sources such as fugitive dust and agriculture and forestry.
c. Selected major air toxics include benzene, formaldehyde, acetaldehyde, 1,3-butadiene, and acrolein.
d. Carbon dioxide emissions are presented as million metric tons of carbon equivalent (MMTCE), a common inventory measure.

Sources: U.S. Environmental Protection Agency and the Energy Information Administration (See endnotes 5 through 9 for complete references.)

Health Effects

Diesel exhaust produces health effects from both short-term (acute) exposure and long-term (chronic) exposures.(4,11) There has only been limited research on the more obvious effects of short-term exposure. Researchers have expended considerable effort trying to determine the health effects of long-term exposure. For long-term exposure, there has been considerable focus on the relationship between diesel exhaust and cancer in both epidemiological and animal studies. Investigators have also looked extensively at noncarcingoenic effects of "pure" diesel exhaust in animal studies. A large body of research exists on the effects of particulates, especially the finer particles, which are thought to lead to greater problems due to their relatively greater ability to move deep into lung tissues.(12,13,14,) Diesel exhaust contains these fine particles and provides precursors to their formation (NO_x, SO_2, and

Figure 1
Areas Where There Is a Risk of Exceeding the One-hour Ozone and PM10 Standards between 2007 and 2030



Note: The triangles and exploding stars on the map show the general area where exceedences with the standards can occur. An area maybe an MSA, CMSA, county, or broader area such as the San Joaquin Valley in California
Source: U.S.EPA, *Regulatory Impact Analysis Heavy-Duty and Vehicle Standards and Highway Diesel Fuel Sulfur Control Requirements*, December 2000

hydrocarbons) in the atmosphere. Especially the high levels of NO_x available from diesel exhaust for transformation make diesel exhaust an even greater contributor to the health effects that have been linked to fine particles.

Effects of Short-Term Exposures

Short-term exposures to diesel exhaust can lead to temporary health effects. These effects include irritation of the eyes, throat, and bronchial tubes, lightheadedness, nausea, coughing, and formation of mucous. There is also some evidence of possible immunologic effects and/or exacerbation of allergenic responses by known allergens.(4,11)

Effects of Long-Term Exposures

The research covering the long-term effects of diesel exhaust considers the potential health effects that may result from diesel exhaust alone and the potential health effects of fine particles, which are a mixture of diesel particulate matter and other particulates from many sources. As mentioned earlier, the NO_x, SO_2, and hydrocarbons in diesel exhaust transform in the atmosphere into fine particles as well as ozone. Researchers have extensively examined the long-term health effects of ozone and the emissions of carbon monoxide and various specific air toxics that are part of diesel exhaust.(15,16,17) The research on diesel exhaust by itself considers the effects of exposure to the mixture of the hundreds of compounds in diesel exhaust, which are often captured by the surrogate measure of diesel particulate matter. Currently, scientists have not been able to isolate within diesel exhaust the specific compounds that are creating the health effects, although they have studied the health effects of many of these constituents individually, such as benzene and other major air toxics mentioned earlier.(4) There are also harmless compounds, such as water vapor, in diesel exhaust and compounds that health scientists simply know little about from a toxicity standpoint.

Diesel Exhaust Alone

Over the last decade, EPA has looked extensively at the scientific literature on the health effects of long-term exposure to diesel exhaust alone and prepared several drafts of a health assessment document (HAD) that has been reviewed by the Agency's Clean Air Act Scientific Advisory Committee (CASAC). In December 2000, the CASAC concurred overall with EPA's health assessment subject to some changes that the Agency is now making in an effort to finalize the HAD in the Spring 2001.(18)

In the diesel exhaust health assessment, EPA finds that diesel exhaust is likely to be carcinogenic to humans by inhalation at occupational and environmental exposure levels.(4) It is likely to cause lung cancer. This characterization is based on the Agency considering all the evidence from human, animal, and other supporting studies. Similar conclusions have been reached by the International Agency for Research on Cancer, the World Health Organization, the U.S. Department of Health and Human Services National Toxicology Program, the National Institute for Occupational Safety and Health, and the California Office of Environmental Health Hazard Assessment.(1)

EPA believes that the current information on cancer effects of diesel exhaust is not sufficient for developing a definitive unit risk factor to use for estimates of cancer cases, although in a risk perspective section of the health assessment the Agency is able to provide a simple sense of what the risk may be - within a range - recognizing the major assumptions and limitations that exist in making such a scientific judgment.(1,4) Despite the uncertainties in today's scientific knowledge, one of the reasons for EPA's recently published emissions controls for heavy-duty engines (in trucks and buses), is the Agency's desire to be prudent in protecting the public against the potential risk of lung cancer. This Agency position exists after the Agency considered the potential magnitude of the risk, exposure of the entire population to various levels of diesel exhaust, consistent observation of significantly increased lung cancer risk in workers exposed to diesel exhaust, and the potential overlap and/or relatively small difference between some occupational settings where increased lung cancer risk is reported and ambient exposures.(1)

EPA has also concluded that long-term exposure to diesel exhaust alone may pose chronic respiratory hazards to humans. This is based on animal studies showing irritation and inflammatory reactions.(4) Epidemiological studies indicate there are similar effects from fine particles.(4)

Pollutants within Diesel Exhaust

Many of the most significant health effects that can be linked to diesel exhaust come from fine particles that are either directly emitted by diesel engines, or formed in the atmosphere from NO_x, SO_2, and hydrocarbons. Substantial health effects also result from ozone formation by NO_x and hydrocarbons. NO_x, SO_2, and CO also have their own direct health effects. There are several air toxic constituents in diesel exhaust that have their own risks of cancer and other health effects. Especially, for fine particles and ozone, over the last decade the Agency has compiled and evaluated extensive amounts of scientific research in EPA's effort to consider possible revisions to the NAAQS.(13,15) For fine particles in particular, over the last year researchers have completed extensive reanalysis of earlier research and new studies have also become available that EPA is carefully evaluating now.(19,20)

With all of this available information, the Agency has made significant progress in estimating quantitatively many of the health effects associated with particulates and ozone levels. Table 2 provides EPA's estimates in its Regulatory Impact Analysis (RIA) of the health benefits that should occur from particulate matter and ozone reductions from the 2007 HDE rule.(12) The analysis is for the year 2030 when all trucks on the road will have been built after 2006 and comply with the standards covering new vehicles. This table's results provide a sense of the significant health impacts that the public could have faced from just truck and bus exhaust in the future, if EPA had not promulgated the 2007 HDE rule. It is important to recognize that for ozone the analysis only covered the Eastern United States where EPA was able to conduct air quality modeling. Importantly, EPA estimates that nonroad mobile sources that use diesel fuel emit substantial levels of the same pollutants that contribute to the fine particle and ozone problems that are highlighted in Table 2.

Table 3 lists other health effects arising from various pollutants within diesel exhaust that EPA could not quantify in its RIA for the 2007 HDE rule.(12) Looking at the two health effects tables together, it is easy to see why EPA and state environmental agencies consider diesel exhaust as one of the most important sources of air pollution today.

Environmental Effects

The pollutants within diesel exhaust can directly or indirectly contribute to significant amounts of environmental damage. Table 4 lists the most apparent environmental damage that EPA believes occurs.(12,21) In this area, the Agency has not been able to quantify much of the environmental damage. However, in support of the 2007 HDE rule, EPA analysis suggests that the public values at more than \$3.3 billion annually the future loss of visibility in just the National Parks in California, the Southwest and Southeast from fine particles formed from diesel exhaust.(12)

It's generally known that diesel engines emit CO_2, the most common greenhouse gas. These emissions contribute to the warming of the earth's atmosphere. An offsetting factor to this is the formation of nitrate and sulfate from the NO_x, SO_2, and hydrocarbon emissions, which in aerosol form in the earth's atmosphere scatter and reflect the sun's heat back into space.(21) Additionally, recent examination of all the key factors that drive the temperature and climate of our atmosphere shows that directly emitted diesel particulates in aerosol form that are largely composed of carbon will both absorb the sun's heat and lead to less reflection of it back into space and reduce cloud cover leading to greater exposure to the sun's heat at the earth's surface.(21) These carbon particles lead to more warming of the atmosphere. Given evidence that aerosol particles are a major factor in influencing climate, the interplay of these offsetting phenomena is under further investigation.

Table 2
Estimates of the Health Effects Prevented Annually in 2030 from the 2007 Heavy-Duty Engine Rule Covering Trucks and Buses

Health Endpoints	Pollutant from Diesel Exhaust	Avoided Cases/Year
Premature mortality (adults, 30 and over)	PM[a]	8,300
Chronic bronchitis (adults, 30 and over)	PM	5,500
Acute bronchitis (children, 8-12)	PM	17,600
Hospital admissions – Pneumonia (adults, 26 and over)	PM	1,100
Hospital admissions- COPD (adults, 64 and over)	PM	900
Hospital admissions – Cardiac Dysrthmias (all ages)	Ozone[b]	300
Hospital admissions – Other Cardiovascular (adults, over 64)	PM	2,700
Hospital admissions – Respiratory Causes (all ages)	Ozone[b]	1,200
Emergency Room Visits for Asthma (65 and younger)	PM, Ozone[b]	300
Asthma Attacks (asthmatics, all ages)	PM, Ozone[b]	361,400
Lower respiratory symptoms (children, 7-14)	PM	192,900
Upper Respiratory symptoms (asthmatic children, 9-11)	PM	193,400
Work loss days (adults, 18-65)	PM	1,539,400
Minor restricted activity days (adults, age 18-65)	PM, Ozone[b]	9,838,500

a. There is epidemiological evidence that ozone and carbon monoxide cause premature mortality, but the EPA is unable to estimate the cases averted at this time in addition to the particulate matter (PM) cases.
b. The estimates for ozone cover only the Eastern United States where modeling of changes from the 2007 HDE occurred.
Source: U.S.EPA, *Regulatory Impact Analysis Heavy–Duty and Vehicle Standards and Highway Diesel Fuel Sulfur Control Requirements*, December 2000.

Table 3
Health Effects Associated with Pollutants from Diesel Exhaust that EPA Has Not Quantified

Health Endpoint	Pollutant from Diesel Exhaust
Chronic asthma	Ozone
Increased airway responsiveness to stimuli	Ozone
Inflammation in the lung	Ozone
Chronic respiratory damage	Ozone
Premature aging of the lungs	Ozone
Acute inflammation and respiratory cell damage	Ozone
Increased susceptibility to respiratory infection	Ozone, NO,
Non-asthma respiratory emergency room visits	Ozone, PM
Infant mortality	PM
Low birth weight	PM
Changes in pulmonary function	PM
Chronic respiratory disease other than chronic bronchitis	PM
Morphological changes	PM
Altered host defense mechanisms	PM
Cancer (including lung cancer and leukemia)	PM, Various Air Toxics
Lung irritation and congestion	NO_x, Acrolein, Diesel Exhaust
Behavioral effects	CO
Developmental effects	CO
Decreased time to onset of angina	CO, 1,3-Butadiene
Reduction of blood platelets, anemia, and disruption of blood production	Benzene
Excessive bone marrow formation	Benzene

Source: Adapted from U.S.EPA, *Regulatory Impact Analysis Heavy–Duty and Vehicle Standards and Highway Diesel Fuel Sulfur Control Requirements*, December 2000

Table 4
Environmental Effects Associated with Pollutants from Diesel Exhaust

Environmental Effect	Pollutants from Diesel Exhaust
Reduced visibility	PM, NO_x, SO_2
Acid rain damage to waterways and forested regions	NO_x, SO_2
Damage to ecosystem functions	Ozone
Eutrophication leads to overgrowth of algae, odor, and fish kills	PM, NO_x
Nitrification of waterways	NO_x
Climate change increasing sea level and altering weather and ecosystems	CO_2 and PM

Source: Adapted from U.S.EPA, *Regulatory Impact Analysis Heavy–Duty and Vehicle Standards and Highway Diesel Fuel Sulfur Control Requirements*, December 2000, and Hansen J, Sato M, Reto R, Lacis A, Oinas V "Global Warming in the Twenty-First Century: An Alternative Scenario," prepublication in the *Proceedings of the National Academy of Science*, 2000.

Economic Effects

Pollutants within diesel exhaust directly or indirectly appear to lower the productivity of our economy. Table 5 lists economic effects from the pollutants in diesel exhaust.(12) In analyzing the effects of the 2007 HDE rule, EPA found that full implementation of that rule could lead to the annual prevention of the loss of more than 1.5 million workdays caused by air pollution from diesel exhaust.(12) This has an annual economic value of $160 million. EPA estimated that ozone reductions resulting from the 2007 HDE rule could increase worker productivity by $140 million annually and increase the output of six major crops at a value of $1.1 billion annually.(12)

In the RIA for the 2007 HDE rule, EPA estimated the total economic value of the health, environmental, and economic benefits, where there are accepted methods for doing so. For the set of pollution changes where benefits could be converted into dollars, EPA found that the annual benefits of full implementation of the HDE rule in 2030 are over $70 billion annually.(12) There also exists the unquantified benefits of reducing other damage mentioned above which EPA believes are substantial. As mentioned earlier, it should also be recognized that this benefits analysis just covers further controls on highway vehicles and substantial emissions of similar pollutants will also result from the operation of nonroad diesel engines.

Table 5
Economic Effects Associated with Pollutants within Diesel Exhaust

Economic Effects	Diesel Exhaust Pollutants
Crop damage lowering productivity	PM, NO_x, SO_2
Forest damage lowering productivity	NO_x, SO_2, Ozone
Damage to urban ornamentals	Ozone
Damage to commercial fisheries and freshwater fishing	NO_x , SO_2, Ozone
Decreased worker productivity	Ozone
Materials damage and household soiling	PM, NO_x, SO_2

Source: Adapted from U.S.EPA, *Regulatory Impact Analysis Heavy–Duty and Vehicle Standards and Highway Diesel Fuel Sulfur Control Requirements*, December 2000.

Conclusion

The air pollutants contained in today's diesel exhaust are associated with many types of serious health, environmental, and economic effects. Quantitative analysis that covers a portion of these effects shows that, if unchecked, future emissions from diesel vehicles could lead to large numbers of health effects and billions of dollars of environmental and economic damage each year. There is a direct association between the pollutants emitted from diesel engines and detrimental effects and an important indirect relationship between the air emissions that are transformed in the atmosphere into other pollutants that are associated with harmful effects. Throughout our economy, diesel engines cost-effectively provide many vital services. Recognizing all of this, EPA wants to work with states, engine manufacturers, the trucking industry, environmental groups, and other stakeholders to provide clean diesel technology in our future.

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