State of California
AIR RESOURCES BOARD

TECHNICAL SUPPORT DOCUMENT FOR PROPOSED ADOPTION OF REGULATIONS LIMITING THE SULFUR CONTENT AND THE AROMATIC HYDROCARBON CONTENT OF MOTOR VEHICLE DIESEL FUEL

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TABLE OF CONTENTS

Page

Page

I. INTRODUCTION

California air quality, as measured by a variety of criteria, is adversely impacted by many emission sources, both mobile and stationary. In varying degrees in various areas, ambient air quality standards are exceeded for ozone, carbon monoxide, nitrogen dioxide, particulate matter, sulfate, and visibility. The Air Resources Board (ARB or Board), as the agency responsible for controlling emissions from motor vehicles, has adopted a number of regulations for vehicle emissions to reduce the impact of motor vehicle emissions on air quality throughout the state.

Among the regulations adopted by the board are performance standards to limit exhaust emissions from motor vehicles and specifications for motor vehicle fuels. Specifications adopted by the Board for gasoline include:

- Volatility limits
- Bromine Number limits (degree of unsaturation)
- Lead content
- Manganese content
- Sulfur content

The Board has also adopted specifications for the sulfur content of motor vehicle diesel fuel sold in the South Coast Air Basin and Ventura County.

As part of the Board's program to reduce further emissions from motor vehicles, we have evaluated several options for diesel fuel specifications that would reduce emissions from the use of diesel fuel in motor vehicles. These options include specifications for the sulfur content and aromatic hydrocarbon content of motor vehicle diesel fuel. This report presents our evaluation of those options and our proposals for regulatory limits on the sulfur content and aromatic hydrocarbon content of motor vehicle diesel fuel.

In developing these proposals for the Board's consideration, the staff held five consultation meetings with interested parties. The notices for those meetings are presented in Appendix A. The consultation meetings were held to discuss the staff's emission inventory, the data available on the relationship between diesel fuel quality and emissions from diesel motor vehicles, the cost of more stringent specifications for motor vehicle diesel fuel, and the form of the staff's regulatory proposal.

This report provides the information that forms the basis of the staff's regulatory proposals. Those proposals include a statewide limit for the sulfur content of 500 parts per million (ppm) for all motor vehicle diesel fuel, and limits on the aromatic hydrocarbon content of motor vehicle diesel fuel. The proposed aromatic hydrocarbon content limits are 10 volume percent for large refiners and 20 volume percent for small refiners.

II. BACKGROUND

A. DIESEL ENGINE OPERATION

Diesel engines have a number of similarities with gasoline engines. Both engine types are fueled by liquid petroleum-derived fuels and they are used in similar applications. Both engine types deliver power by rapidly burning fuel in a combustion chamber to apply a downward force on a piston within a cylinder. The up and down motion of the piston(s) is converted to a rotating motion by means of a crankshaft. Multi-piston engines of both the gasoline and diesel type have similar cylinder positioning within the engine block.

The main difference between spark-ignited engines and diesel engines is the method of initiating fuel combustion. Spark-ignited engines rely upon an external source of energy to initiate the combustion of fuel and air within the engine cylinder. This energy is provided by the spark plug as the terminal element in the engine's electrical ignition system.

Diesel engines rely upon the fuel to self-ignite upon reaching the proper air/fuel ratio, temperature, and pressure. Diesel fuel is injected under high pressure into the diesel engine's cylinders as the piston approaches the top of the combustion chamber. The compression of the air within the cylinder causes the temperature as well as the pressure to rise sufficiently to cause the fuel/air mixture to ignite.

As with spark-ignited engines, diesel engines may be described as either two-stroke or four-stroke engines. The two-stroke and four-stroke cycles are shown in Figure 1. The four stroke cycle shown in the figure is familiar to most and follows the same stroke cycle as the gasoline-fueled automobile engine. The two-stroke cycle shown in Figure 1 is less familiar and deserves a brief discussion.

In the two-stroke cycle, the compression and power strokes are identical to those of the four-cycle engine. In the two-cycle engine, however, exhaust gases are removed from the cylinder and fresh combustion air are brought into the cylinder in one step. The device shown on the left of the cylinder in Figure 1's depiction of the two-stroke cycle is a blower that introduces fresh air into the cylinder. That fresh air forces out the exhaust gases and results in a fresh "charge" of combustion air. The cylinder is then ready to receive another injection of fuel as the piston completes another compression stroke.

Most diesel vehicles are powered by four-stroke engines. The ARB staff estimates that about 90 percent of heavy-duty diesel vehicle engines used in California are four-stroke engines and virtually all diesel passenger cars are four-stroke engines.

In a gasoline engine, the fuel handling and metering equipment consists primarily of a carburetor, throttle body injection system, or manifold injection system, which adjusts the air/fuel ratio in accordance with operating requirements, i.e.,

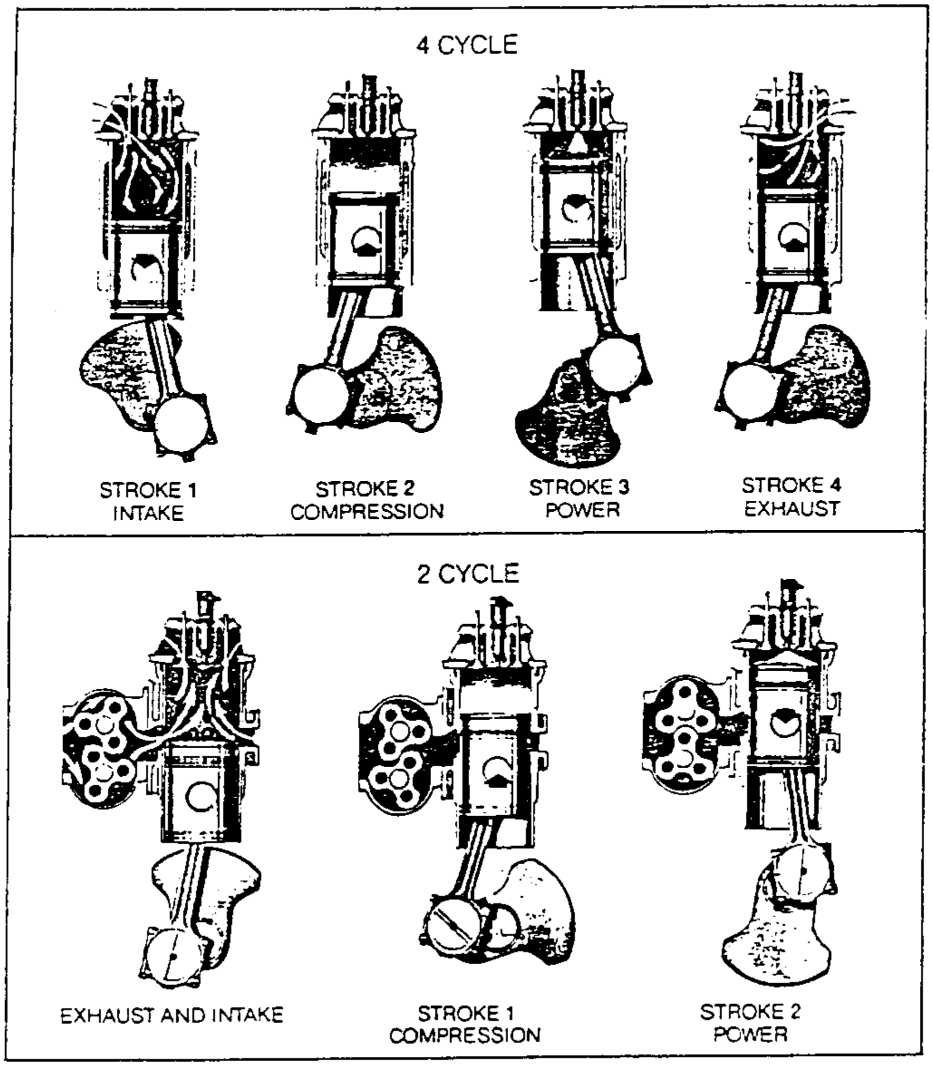


Figure 1

Diesel Four-Stroke and Two-Stroke Cycles

Source: Detroit Diesel Allison Division of General Motors, Advertising Brochure, "There Is a Difference in Diesels."

rich for idle and acceleration, and lean for cruising. In a diesel engine, the amount of air taken in prior to the compression stroke is fixed. The amount of fuel delivered to the cylinder depends on the engine speed and the input of the operator via the accelerator mechanism. Injection timing is, however, automatically adjusted as a function of engine speed and load.

B. DIESEL VEHICLE FUELS

Diesel engine fuel requirements are different than those for gasoline engines. Gasoline engines require fuel with a minimum octane number. The octane number is a measure of the resistance of fuel to auto-ignite. In a gasoline engine, it is desirable for auto-ignition not to occur because the proper operation of the engine depends on ignition occurring when the spark plug fires.

In a diesel engine, it is desirable to have a fuel that readily ignites under the conditions that prevail in the engine's cylinders. That quality is measured by the cetane number and it is important for the proper operation of a diesel engine to have fuel with a minimum cetane number. Other diesel fuel qualities that affect the operation of diesel engines in cold weather and the long-term durability of diesel engines include pour point, viscosity, sulfur content, and 90 percent distillation temperature. The pour point is the temperature at which a fuel is able to flow and should not be confused with viscosity. Viscosity is the measure of a fluid's resistance to flow while the pour point, important in cold climates, is the temperature below which the material will not flow at all. The 90 percent distillation temperature, often called the 90 percent point, is the temperature at which 90 percent of the fuel will have boiled away.

Diesel fuel can be made from any number of components that are produced in an oil refinery. The American Society for Testing and Materials (ASTM) has set specifications for diesel fuels. Some states, including California, have adopted those specifications as legal requirements. The ASTM specifications for No. 1 diesel and No. 2 diesel, the most common high and medium speed diesel engine fuels, are shown in Table 1.

Diesel fuels may be produced from refinery streams that have the qualities required to meet the ASTM specifications in Table 1. No. 2 diesel fuel is produced from hydrocarbon stocks that are referred to as gas oils. No. 1 diesel fuel is produced from refinery streams that lie in the kerosene boiling range. All fuels that lie within the boiling range of No. 1 and No. 2 diesel fuel are referred to generically as "distillate." Because No. 2 diesel fuel represents the bulk of the diesel fuel produced and used in California, the remainder of this report addresses only that fuel.

A refinery stream component that can be used to produce diesel fuel is atmospheric gas oil, also referred to as straight run gas oil. This is the diesel boiling range material that occurs naturally in the crude oil and is separated from the other

TABLE 1 Detailed Requirements for Diesel Fuel Oils [A,H]

Grade of Diesel Fuel Oil		Flash Point, °C (°F)	Cloud Point, °C	Water and Sediment, vol %	Carbon Residue on, 10 % Residuum, %	Ash, weight %	Distillation Temperatures, °C (°F) 90 % Point		Viscosity Kinematic, cSt[G] at 40°C		Viscosity Saybolt, SUS at 100°F		Sulfur,[D] weight %	Copper Strip Corrosion	Cetane Number[E]
		Min	Max	Max	Max	Max	Min	Max	Min	Max	Min	Max	Max	Max	Max
No. 1-D	A volatile distillate fuel oil for engines in service requiring frequent speed and load changes	38 (100)	[B]	0.05	0.15	0.01	...	288 (550)	1.3	2.4	...	34.4	0.50	No. 3	40[F]
No. 2-D	A distillate fuel oil of lower volatility for engines in industrial and heavy mobile service	52 (125)	[B]	0.05	0.35	0.01	282[C] (540)	338 (640)	1.9	4.1	32.6	40.1	0.50	No. 3	40[F]
No. 4-D	A fuel oil for low and medium speed engines.	55 (130)	[B]	0.50	...	0.10	...	...	5.5	24.0	45.0	125.0	2.0	...	30[F]

[A] To meet special operating conditions, modifications of individual limiting requirements may be agreed upon between purchaser, seller, and manufacturer.

[B] It is unrealistic to specify low-temperature properties that will ensure satisfactory operation on a broad basis. Satisfactory operation should be achieved in most cases if the cloud point (or wax appearance point) is specified at 6°C above the tenth percentile minimum ambient temperature for the area in which the fuel will be used. The tenth percentile minimum ambient temperatures for the United States are shown in Appendix X2. This guidance is of a general nature; some equipment designs, use flow improver additives, fuel properties, or operations, or a combination thereof, may allow higher or require lower cloud point fuels. Appropriate low temperature operability properties should be agreed upon between the fuel supplier and purchaser for the intended use and expected ambient temperatures.

[C] When cloud point less than −12°C (10°F) is specified, the minimum viscosity shall be 1.7 cSt (or mm²/s) and the 90 % point shall be waived.

[D] In countries outside the United States, other sulfur limits may apply.

[E] Where cetane number by Method D 613 is not available, Method D 976 may be used as an approximation. Where there is disagreement, Method D 613 shall be the referee method.

[F] Low-atmospheric temperatures as well as engine operation at high altitudes may require use of fuels with higher cetane ratings.

[G] 1 cSt = 1 mm²/s.

[H] The values stated in SI units are to be regarded as the standard. The values in inch-pound units are for information only.

Source: 1988 Annual Book of ASTM Standards crude oil components in a crude oil distillation column. The crude is distilled in the distillation column at near atmospheric pressure, hence the appellation "atmospheric gas oil." This is the only diesel fuel component available to refiners that do not have the facilities to convert heavier crude oil components to lighter, more valuable fuels. Complex refineries have such conversion facilities. Such facilities would currently be in use to produce a refinery's present product mix.

Figure 2 is a complex refinery configuration and flow chart. Although not all complex refineries have all of the processes shown in the figure, the figure shows a range of processes that are used, and the variety of hydrocarbon streams available for finished product blending.

Complex refineries have cracking processes that produce gas/oil streams that may be blended into diesel fuel. Those processes include fluid catalytic cracking, thermal cracking (including coking), and hydrocracking. Hydrocracking can, depending on the characteristics of the feed, produce a hydrocarbon stream that has desirable characteristics for diesel fuel blending. Depending on the feed quality, the aromatic hydrocarbon content of hydrocracked products can be low and, as such, demonstrate desirable ignition characteristics. Hydrocracked products are also low in sulfur. The use of hydrocracked material in the diesel fuel boiling range must, however, compete with other demands such as further processing to jet fuel or gasoline. Gas oils from fluid catalytic cracking and

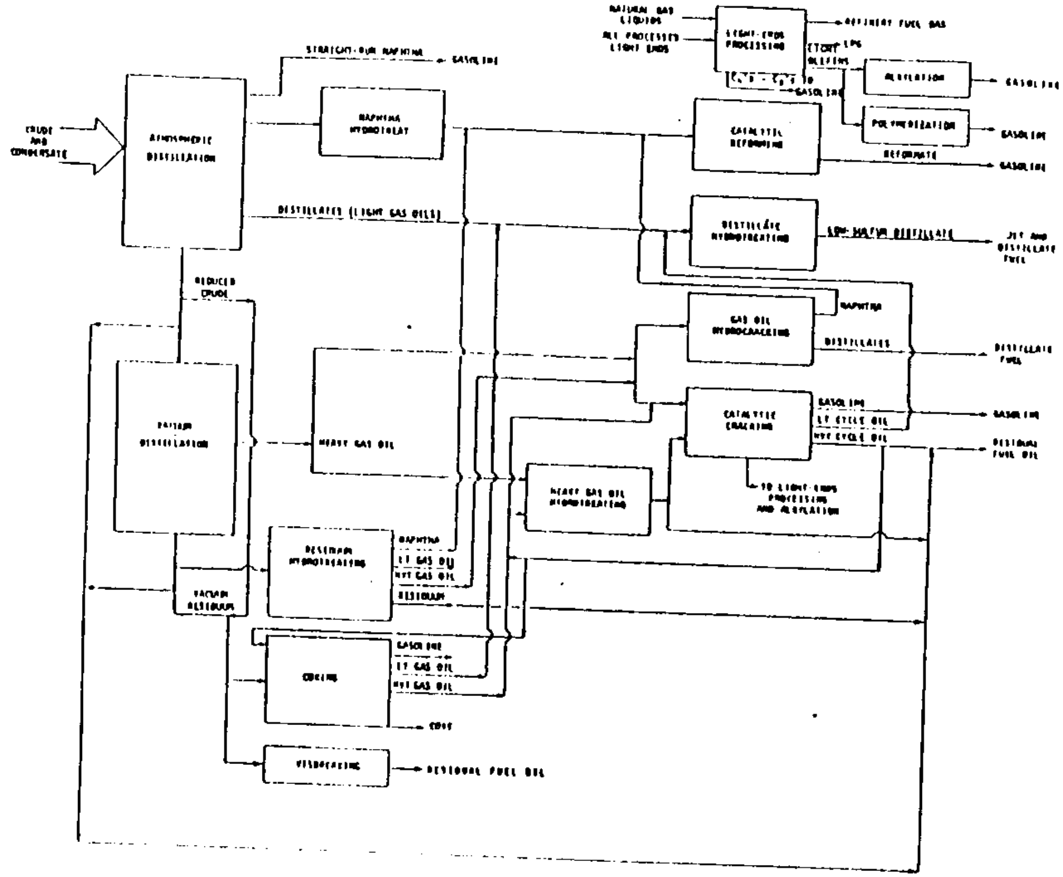


Figure 2

Complex Refinery Configuration

Source: Bonner and Moore, 1985 Oil Scenario Study thermal cracking are poor diesel blending stocks because they are generally high in sulfur and aromatic hydrocarbon, have poor ignition qualities, and are less stable in storage than straight-run gas oils.

C. EXISTING DIESEL VEHICLE STANDARDS

The Board has adopted emissions standards for diesel vehicles. In August 1982, the Board adopted particulate matter emissions standards for 1985 and later model year diesel passenger cars, light-duty diesel trucks and medium-duty diesel vehicles. These groups of vehicles are also subject to the same hydrocarbon, carbon monoxide, and NO_x emission standards that apply to gasoline-powered vehicles.

In April 1986, the Board adopted emissions standards for heavy-duty diesel engines. The heavy-duty diesel engine standards correspond to the federal emissions standards promulgated by the EPA in 1985. The gaseous emissions standards for heavy-duty diesel engines are: 1.3 grams of hydrocarbon per brake-horsepower-hour and 15.5 grams of carbon monoxide per brake-horsepower-hour for all model years after 1986, 6.0 grams of NO_x per brake-horsepower-hour for 1988 and 1989 model years, and 5.0 grams of NO_x per brake-horsepower-hour for all model years after 1989. The diesel vehicle particulate matter emissions standards adopted by the Board are summarized in Table 2.

Table 2

California Diesel Vehicle Particulate Matter Emission Standards

Model Years	Passenger Cars, Light-Duty Trucks, Medium-Duty Vehicles (Grams/Mile)	Heavy-Duty Engines (Grams/Brake-Horse-Power-Hour)
1982-1984	0.6	None
1985	0.4	None
1986	0.2	None
1987	0.2	0.60 (optional)
1988	0.2	0.60
1989	0.08	0.60
1990	0.08	0.60
1991	0.08	0.25 (0.10 for Urban Bus Engines)
1992	0.08	0.25 (0.10 for Urban Bus Engines)
1993	0.08	0.25 (0.10 for Urban Bus Engines)
1994 and Later	0.08	0.10 (All Engines)

Source: ARB/SSD/MSD

D. EXISTING SULFUR CONTENT REGULATION

In April 1981, the staff presented for the Board's consideration a proposed regulation to limit the sulfur content of motor vehicle diesel fuel to 500 parts per million by weight (ppm). At the April hearing, the Board directed the staff to modify the proposal such that it would apply to motor vehicle diesel fuel sold in the South Coast Air Basin (SCAB) and Ventura County, and to provide for limited exemptions from the sulfur limitation for small refiners, that is, refiners with crude oil capacities less than 50,000 barrels per day.

In July 1981, at the hearing continued from April, the Board adopted the staff's modified proposal as amendments to Section 2252, Title 13, California Administrative Code (now the California Code of Regulations). Section 2252, as amended, required diesel fuel for use in motor vehicles in the SCAB and Ventura County to contain no more than 500 ppm sulfur. Individual small refiners were exempt from the requirement up to a maximum annual production volume that was equal to 120 percent of the small refiner's highest annual production in the three year period 1978 to 1980.

In October 1984, the staff presented a status report to the Board on diesel engine emission reductions that could be achieved through modifications to motor vehicle diesel fuel specifications. At the October meeting, the Board directed the staff to prepare proposed amendments to Section 2252 to limit the volume of exempt motor vehicle diesel fuel produced by small refiners. In response to that directive, the staff presented to the Board at a public hearing in April 1985, options for amendments to Section 2252 that would reduce the volume of diesel fuel exempt from the sulfur limitation of Section 2252. After continuing the hearing to June 1985, and considering additional information at the June Board meeting, the Board adopted amendments to Section 2252 that reduced the small refiners exempt volume of motor vehicle diesel fuel, and terminated the exemption provisions effective January 1, 1989.

E. RECENT INVESTIGATIONS

Since the Board's adoption of amendments to Section 2252, the staff has continued to investigate emission reductions that could be realized from control strategies for diesel vehicles and fuels.

To obtain the best available information regarding the effects of fuel quality on diesel engine emissions, we have participated in a study being sponsored by the Coordinating Research Council (CRC). The CRC study is evaluating the emissions-fuel quality relationship by testing a variety of fuels in three heavy-duty diesel engines. The ARB has provided partial funding for the study and we have participated on the steering committee for the project.

The ARB has contracted with Arthur D. Little, Inc. (ADL) to perform a linear programming analysis of the cost to produce diesel fuel with different fuel qualities. The ADL study provides models of the California refining industry to determine the refining process options and the associated costs that would be related to new standards for motor vehicle diesel fuel.

III. NEED FOR DIESEL VEHICLE EMISSION REDUCTIONS

Diesel motor vehicles are contributors to a variety of air quality problems in California. Among the air quality standards that are exceeded and to which emissions from diesel motor vehicles contribute to the exceedences are:

- o Particulate matter
- o Nitrogen Dioxide
- o Sulfate
- o Ozone
- o Visibility

In addition, emissions from diesel motor vehicles contribute to the formation of acid precipitation.

The pollutant species for which diesel vehicles are of major concern as emission sources are sulfur dioxide, particulate matter and oxides of nitrogen. We estimate that, statewide in 1990, diesel motor vehicles will account for 97 tons per day of sulfur dioxide emissions, 98 tons per day of particulate matter emissions, and 706 tons per day of oxides of nitrogen emissions. These emissions represent about 17 percent of all sulfur dioxide emissions, 4 percent of particulate matter emissions, and about 25 percent of oxides of nitrogen emissions. These are even greater percentages when compared to the part of the total emissions from motor vehicles.

As discussed further in Chapter VIII and IX of this report, various investigators have found that diesel fuel quality affects emissions from diesel motor vehicles. A number of evaluations show the relationship between increased aromatic hydrocarbon content of diesel fuel and increased emissions of particulate matter and oxides of nitrogen from diesel engines. Emissions of sulfur dioxide are a function of the sulfur content of fuel. The sulfur content of diesel fuel is much higher than that of gasoline except in the South Coast Air Basin where the Board has established a limit for motor vehicle diesel fuel sulfur content.

The air quality impacts of oxides of nitrogen emissions include directly affecting ambient concentrations of nitrogen dioxide, participating in the ozone formation reaction, and contributing to ambient fine particulate matter concentrations. The air quality impacts of sulfur dioxide emissions include directly affecting ambient concentration of sulfur dioxide and sulfate and contributing to ambient fine particulate matter. Emissions of both oxides of nitrogen and sulfur dioxide contribute to reductions in visibility and formation of acid precipitation.

Diesel vehicles are sources of both directly emitted particulate matter in the form of soot, and precursors to secondary particulate matter (sulfates and nitrates) in the form of sulfur dioxide and oxides of nitrogen. Most of the particulate matter that results from combustion in diesel engines, both secondary particulate matter formed in the atmosphere and directly emitted, is in the fine particulate matter (PM_{10}) size range. The PM_{10} air quality problem may be the most intractable air quality problem in California. The federal standards for PM_{10} are exceeded in four of the state's air basins while the state standard for PM_{10} is violated in virtually the entire state.

A large body of data from animals and humans indicates that exposure to PM-10 can interfere with the respiratory system. Specific effects include: changes in gas exchange or circulation, alteration of respiratory defense mechanisms, decreased pulmonary function, narrowing of air passages, and inflammation due to cell damage in the lungs.

Several epidemiological studies have demonstrated that acute daily exposures to PM-10 are associated with increased mortality, respiratory illness, bronchoconstriction, increases in asthma attacks, increases in hospital and emergency room visits, and decrements in pulmonary function. Chronic exposure to PM-10 in humans has been reported to decrease pulmonary function, while studies of chronic exposure in children have also shown increased incidence in respiratory illness.

The reduction of emissions from diesel motor vehicles is one of the strategies that can be implemented toward attaining the federal PM_{10} standard and to move toward achieving the state PM_{10} standard.

Diesel exhaust is thought to contain well over 1000 compounds, of which over 100 have been identified. Many of the identified compounds are known carcinogens and/or mutagens. These toxic compounds are found both in the particle phase (such as many of the polycyclic aromatic hydrocarbons) and in the vapor phase (such as benzene and formaldehyde). Benzene causes leukemia in workers exposed to the solvent vapors and formaldehyde has been shown to cause lung tumors in rats when inhaled. A class of compounds present in both diesel and automobile exhaust is the nitro-polycylic aromatic hydrocarbons or nitro-PAHs for short. Nitro-PAHs are found in both the particle and vapor phase and many are potent mutagens in bacterial short-term genotoxicity tests. Many of the nitro-PAHs are also animal carcinogens.

In addition to contributing to the variety of air quality problems discussed above, emissions of soot, in the form of smoke, from diesel vehicles elicit a strong negative response from the public. We have received a number of letters from mayors of cities in Southern California urging that steps be taken to provide a cleaner diesel fuel to reduce emissions from diesel vehicles. Those letters are presented in Appendix B.

IV. EMISSIONS FROM DIESEL VEHICLES

A. STATEWIDE INVENTORY - PRESENT

The ARB staff conducted a public consultation meeting in December 1987 to discuss a draft inventory of emissions from diesel-powered motor vehicles and the methodology used to develop the inventory. The inventory included emissions from on-road as well as from off-road diesel motor vehicles. The off-road motor vehicle category includes only diesel powered off-road farm and non-farm mobile equipment.

Draft inventories with supporting documentation were sent to interested parties soliciting comments and no adverse comments were received. The results of this inventory projected for the year 1990, are shown in Table 3 and Figure 3.

As shown in Figure 3, the statewide emission projections for 1990 for diesel vehicles represent 66 percent of the PM_{10} emissions of all mobile sources, 36 percent of the NO_x emissions from all mobile sources, and 45 percent of the SO_2 emissions from all mobile sources. The projected emissions from diesel motor vehicles for 1990 represent about 20 percent of the statewide PM_{10} inventory (other than emissions from fugitive sources), about 25 percent of the statewide NO_x mobile source inventory, and about 17 percent of the statewide SO_2 inventory. The SO_2 emission estimates shown in this Table 3 and Figure 3 are based

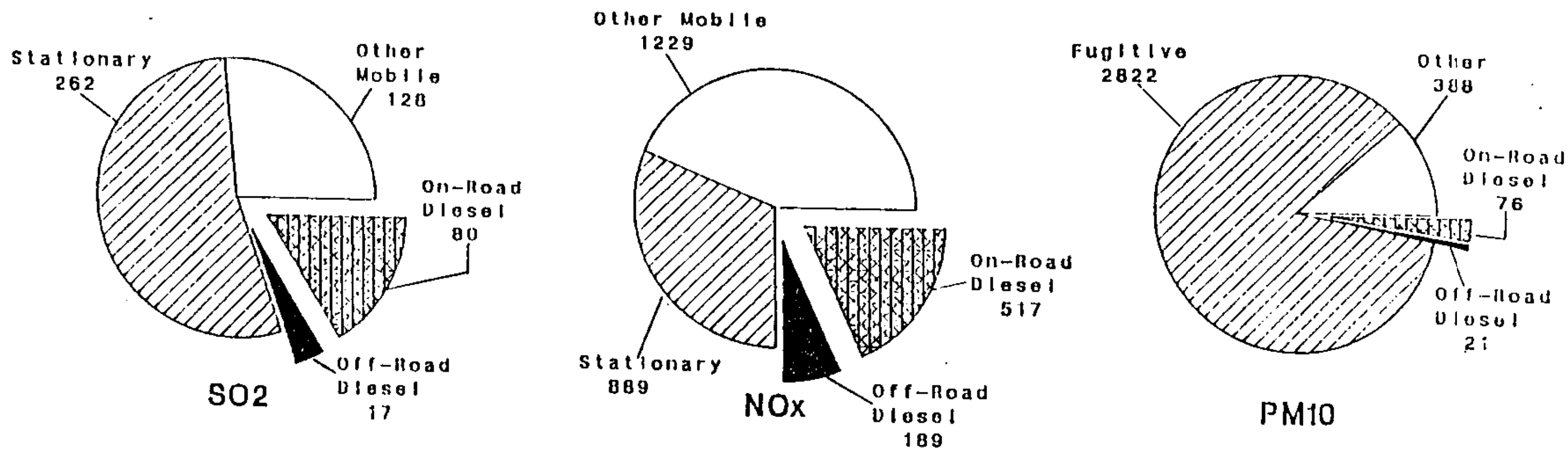
Table 3
Estimated Statewide Emissions
(Tons Per Day)
1990

Source Category	SO_2	NO_x	PM10 Fugitive	PM10 Other
		Pollutant		
Total	555	2877	2845	488
Stationary	339	945	2783	342
Mobile	216	1932	62	146
Diesel Vehicles				
Total	97	706	9	97
On-Road	80	517	9	76
Off-Road	17	189	0	21

Source: ARB/SSD/TSD

Figure 3

1990 Projected Statewide Emissions*
Tons per Day



* No controls beyond what exists in 1989.

Source: ARB/SSD/TSD

on the estimated fuel use as shown in Table 4. We project that the demand for diesel fuels will increase by 26 percent from the year 1990 to the year 2010. The SO_2 estimates presented in this table are based on the assumption that the diesel fuel used in the SCAB contains 0.05 percent sulfur by weight versus the 0.28 percent sulfur content for diesel fuel assumed for other areas of the state.

B. STATEWIDE INVENTORY - FUTURE

Using the projections for the diesel fuel use and the ARB staff estimates on future growth on diesel vehicles, we have projected the diesel motor vehicle emissions up to the year 2010. These projections incorporate the impacts of the 1991 and 1994 heavy-duty emission standards, the estimates of the impacts of tampering and malmaintenance within the heavy-duty diesel fleet, as well as the estimates of the impacts of the expected improvements in fuel economy. However, it excludes the impact of tampering and malmaintenance for 1991-1994 because it assumed that engine manufacturers will be able to meet the 1991 standards by engine modifications alone. Figures 4 and 5 show the estimated statewide emissions for NO_x and PM for the years 1990 through 2010. The figures show a continuous growth in NO_x emissions and a decrease in PM emission starting from 1990 to the year 2000. The decline in PM emissions is due to the effect of the 1991 and 1984 PM standards for on-road heavy duty diesel vehicles. The inventory shows an emissions minimum to be reached in the period of the years 2000-2005 and then an emissions

Table 4

Projected Statewide and SCAB Motor Vehicle Fuel Use

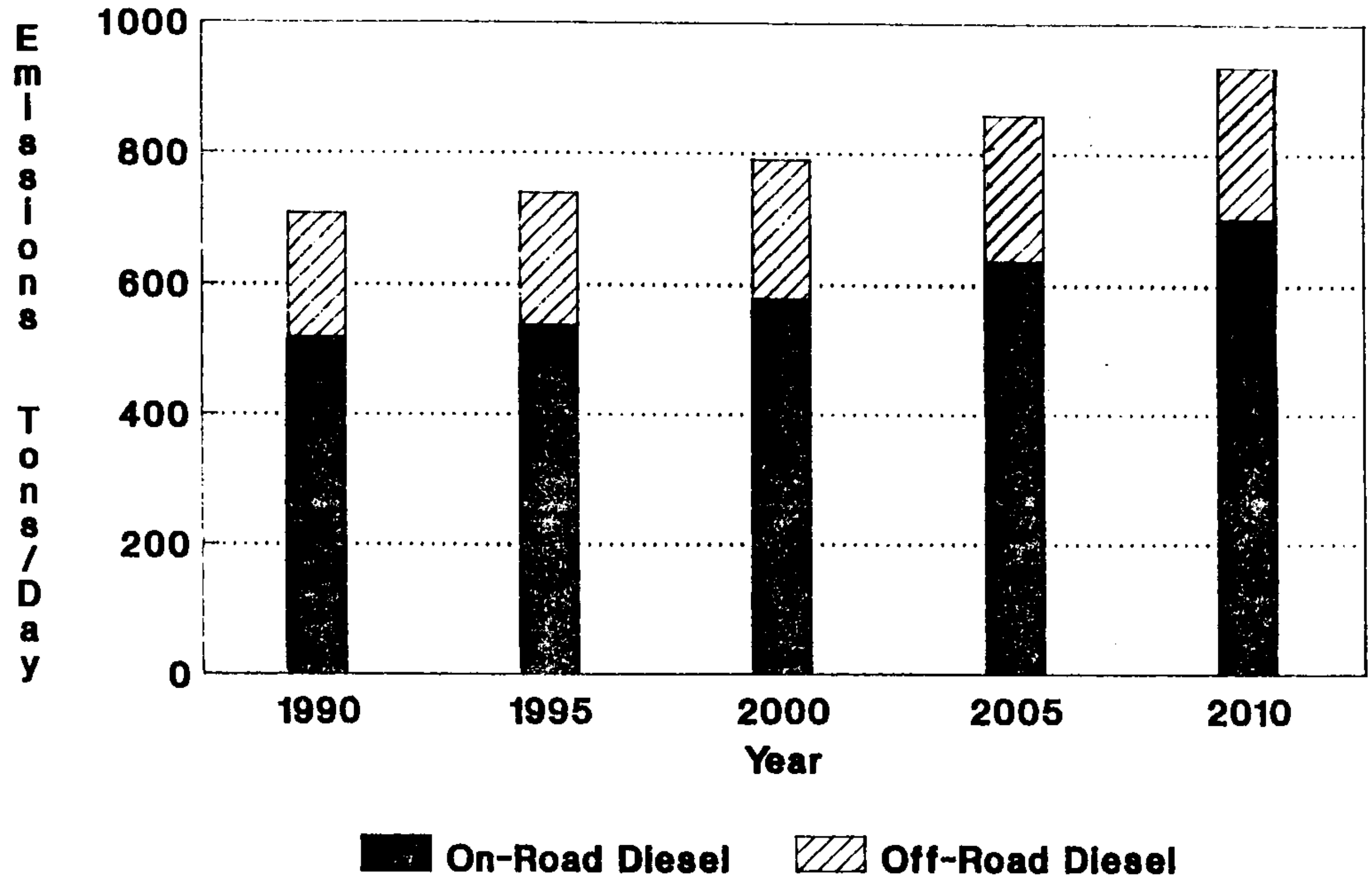
	Statewide Diesel Fuel Use (Barrels*/Day)	SCAB Diesel Fuel Use (Barrels/Day)
1990	153,000	45,000
1995	163,000	47,000
2000	170,000	47,000
2005	180,000	49,000
2010	193,000	52,000

* Barrel is 42 gallons

Source: ARB/SSD/TSD

Figure 4

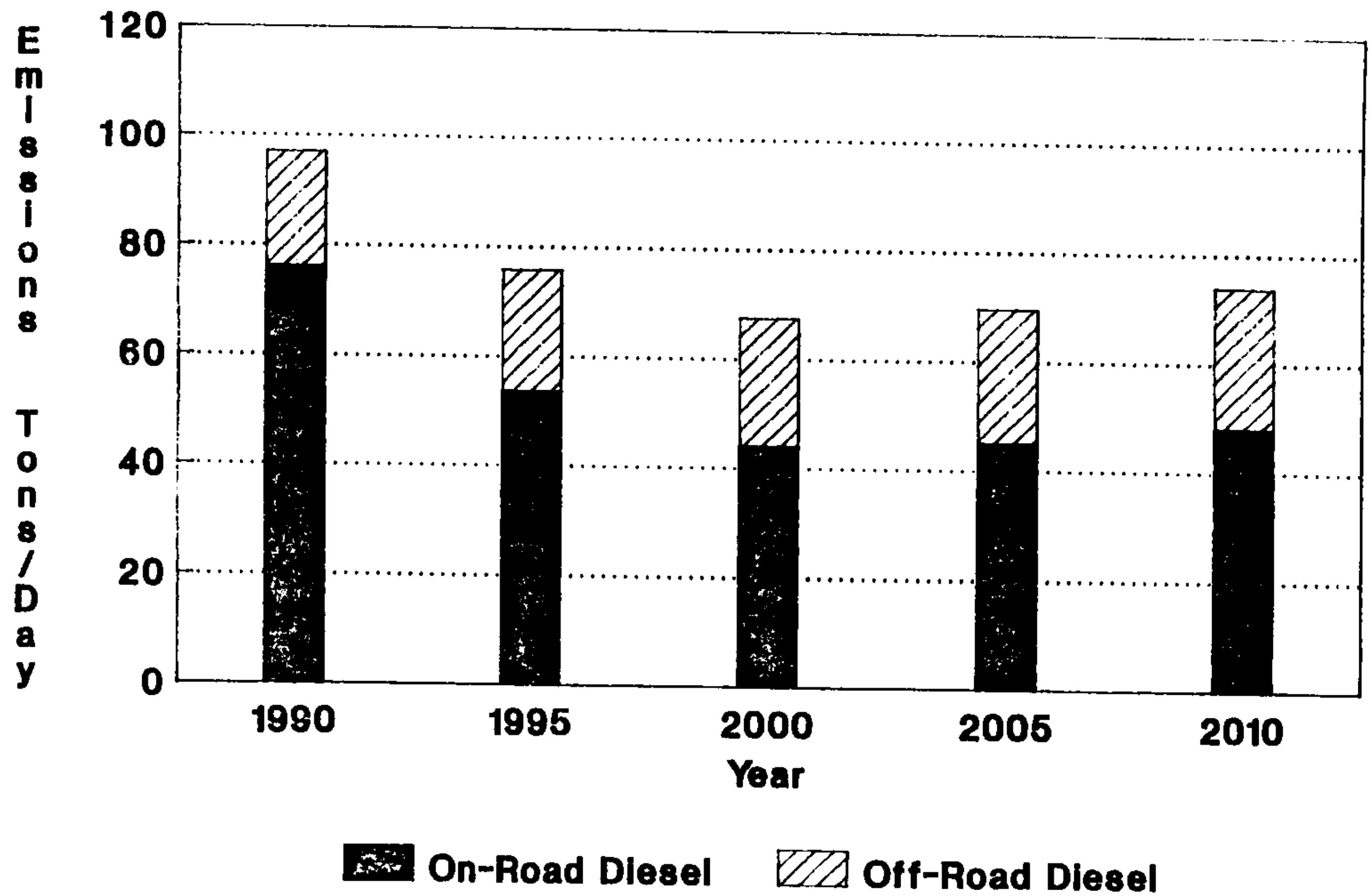
Projected Statewide Inventory of
NOx Emissions from Diesel Motor Vehicles



Source: ARB/SSD/TSD/MSD

Figure 5

Projected Statewide Inventory of PM10 Emissions from Diesel Motor Vehicles



Source: ARB/SSD/TSD/MSD

increase. Off-road emissions are continuously increasing at a rate of 5 percent for every five year time period.

C. SOUTH COAST AIR BASIN INVENTORY - PRESENT

The inventories of emissions from diesel motor vehicles for the SCAB for the year 1990 are shown in Table 5 and Figure 6. The SCAB inventory presented in this table shows the same trends for NO_x and PM emissions as shown in the statewide inventory. However, the SO_2 emissions estimates shown here are disproportionaly lower than the fuel consumption shown in Table 4. This is due to the effect of the sulfur regulation for the SCAB that limits the sulfur content of diesel fuel used for motor vehicles to 0.05 percent by weight.

D. SOUTH COAST AIR BASIN INVENTORY - FUTURE

Figures 7 and 8 show the ARB's projections for SCAB for NO_x and PM from diesel powered motor vehicles for the years 1990 through 2010.

Again, as in the statewide inventory, PM emissions projections show a maximum benefit of implementing the heavy-duty vehicle standards through the year 2005 and then the benefits start declining.

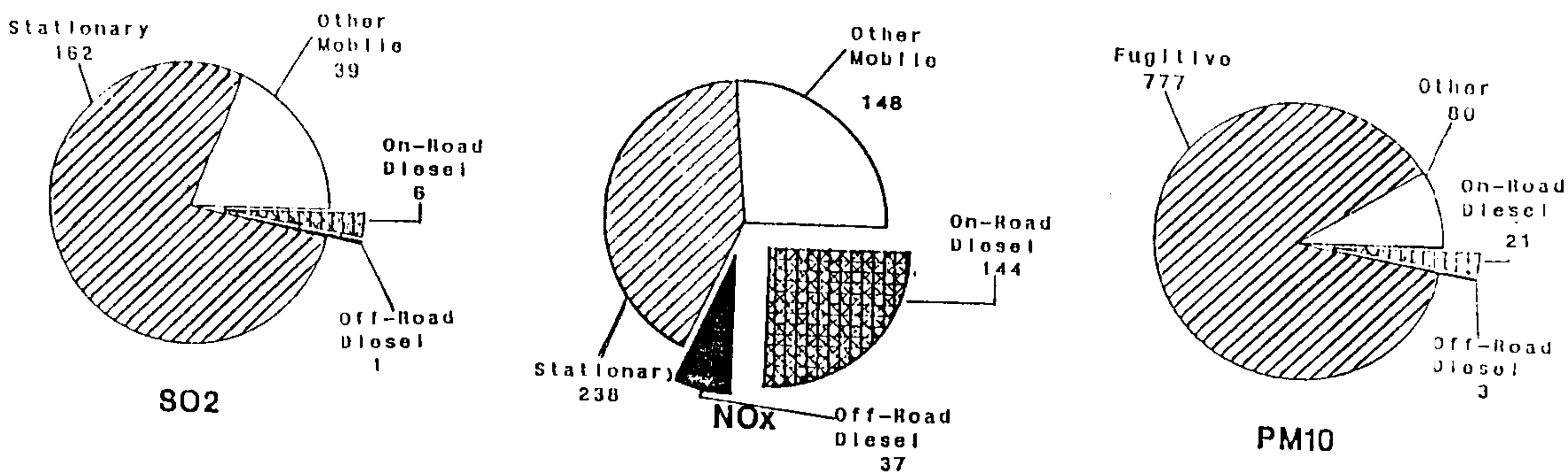
Table 5

South Coast Air Basin Estimates
of Emissions (Tons/Day)
1990

Source Category	Pollutant			
			PM_{10}	
	SO_2	NO_x	Fugitive	Other
Total	201	567	777	79
Stationary	162	238	716	42
Mobile	39	329	61	37
Diesel Vehicles	7	181	3	24
On-Road	6	144	3	21
Off-Road	1	37	0	3

Source: ARB/SSD/TSD

Figure 6
1990 Projected SCAB Emissions*
Tons Per Day

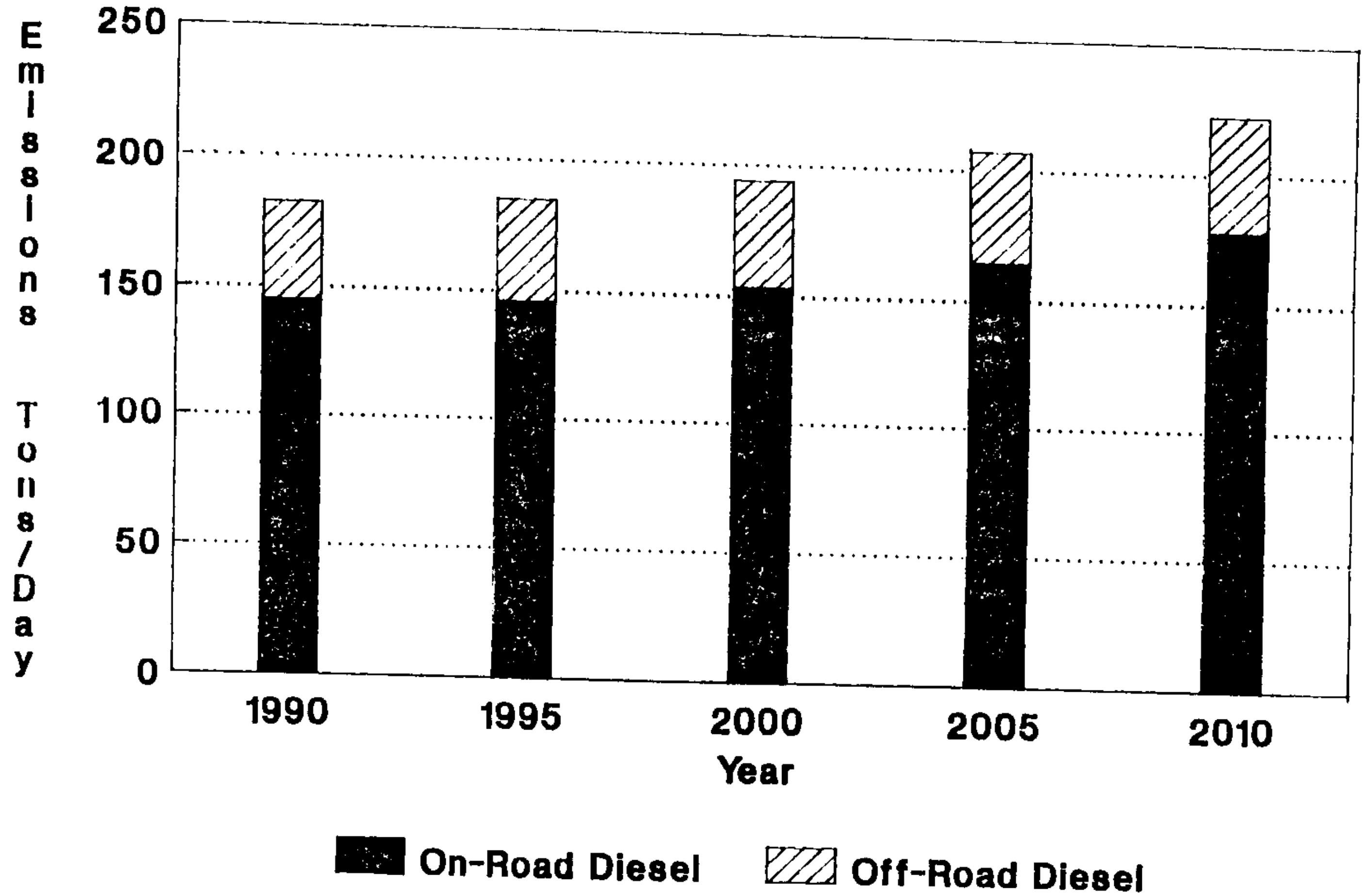


* No controls beyond what exists in 1989.

Source: ARB/SSD/TSD

Figure 7

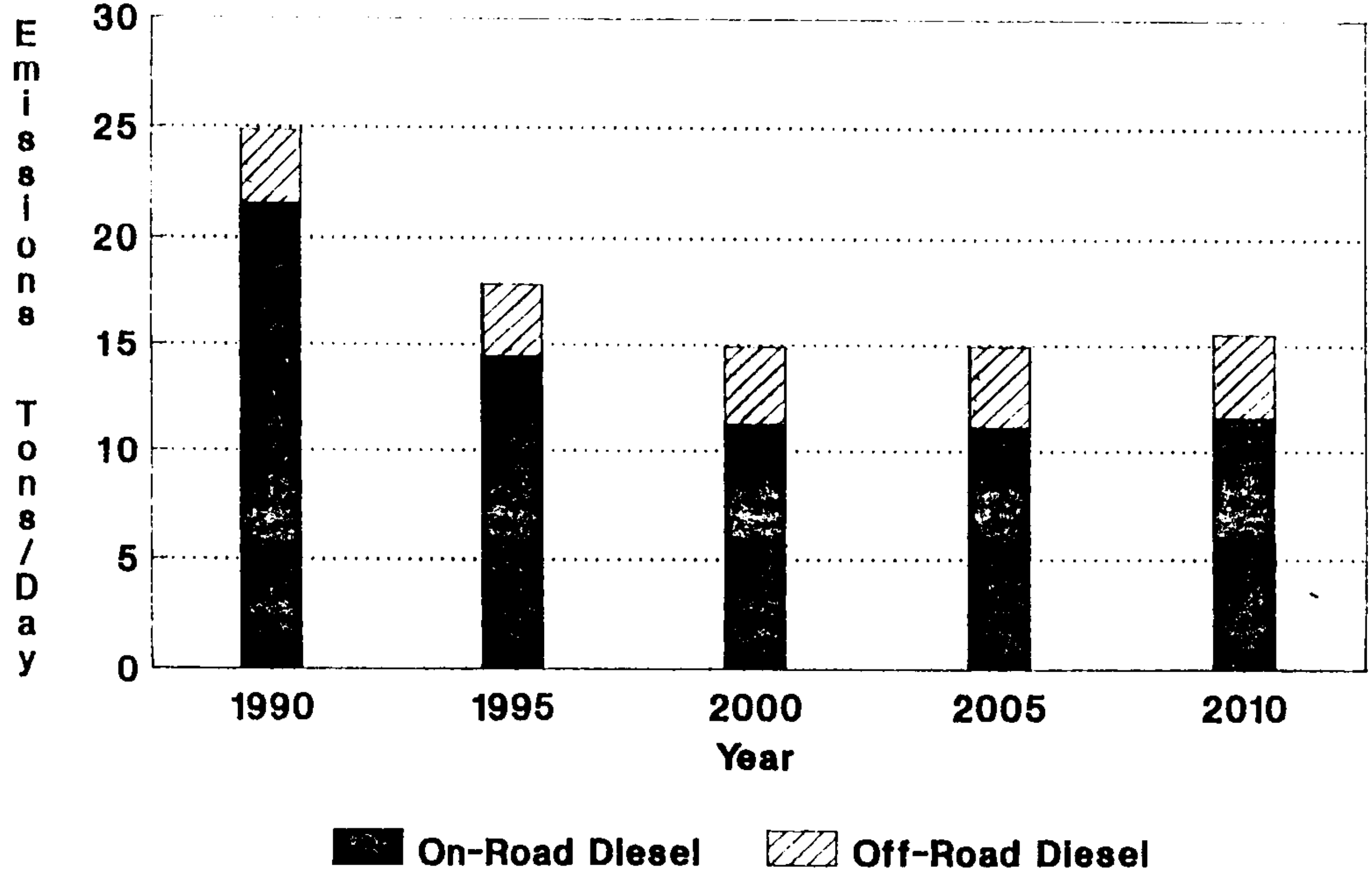
Projected SCAB Emission Inventory for NOx from Diesel Motor Vehicles



Source: ARB/SSD/TSD/MSD

Figure 8

Projected SCAB Emission Inventory for PM10 from Diesel Motor Vehicles



ARB/SSD/TSD/MSD

V. DIESEL VEHICLE EMISSION REQUIREMENTS

A. VEHICLE STANDARDS

Standards for heavy-duty diesel vehicle (HDDV) emissions which will require engine modifications and exhaust treatment devices have been adopted by the U.S. Environmental Protection Agency (EPA) and the ARB. These standards limit HDDV PM emissions to 0.25 g/bhp-hr in 1991 (with urban transit buses limited to 0.10 g/bhp-hr) and 0.10 g/bhp-hr in 1994. NO_x emissions are limited to 5.0 g/bhp-hr beginning in 1991.

Most HDDV manufacturers are relying on engine and fuel system modifications to conventional diesel engines fuel to meet the 0.25 g/bhp-hr standard, although limited trap useage has been predicted by some. Some manufacturers appear to have developed prototype engines that have been shown to be capable of meeting the 1991 standards or come very near to the standards. However, no data exist clearly showing that prototype engines can "comfortably" meet the 1991 standards. This is important because prototype and certification systems generally have lower emissions than production systems and indicates that engine modifications may be adequate for an engine to be certified, but may not allow a sufficient margin for engines to continue to meet the standards in use. However, it is generally thought that at least some HDDV engines will be capable of meeting the 1991 PM standard through the use of engine modifications alone and that no real problems exist that will preclude most HDDV engines from meeting the 0.25 g/bhp-hr standard.

The major focus of efforts to meet the 1994 PM standard has been the development of particulate matter traps. The development of trap technology has been slower than expected and numerous problems with trap usage have been observed. Most of the problems with traps can be linked to one of the following:

1. Fuel Sulfur
2. Low Particulate Collection Efficiency
3. Irregular Regeneration

Sulfur compounds in the exhaust are converted to sulfur dioxide and particulate sulfates by both catalyzed and uncatalyzed traps. With uncatalyzed traps, the sulfate generated in the engine is initially retained in the trap and then later released. With catalyzed traps employing noble metal catalysts, other sulfur containing species are converted to sulfate by the trap. The generation of sulfate particles often causes the calculated efficiency of the trap (efficiency is usually defined as the mass of tailpipe out PM divided by the mass of engine out PM) to be near zero or even negative. This results from carbonaceous particles have been exchanged for sulfate particles.

Trap regeneration in uncatalyzed traps is a problem for HDDV because exhaust temperatures are often below the minimum temperature needed for trap regeneration. Traps become plugged with PM creating excessive back pressure. When a heavily loaded or partially plugged trap finally regenerates, overheating may occur accompanied by trap failure due to cracking. This is less of a problem for catalyzed traps than for uncatalyzed traps because the use of a catalyst lowers the temperature required for regeneration thus, allowing more frequent regeneration. The cost of reducing PM emissions with traps (assuming the problems discussed above are solved) depends heavily on the assumptions made regarding the baseline emission levels of HDDV, trap life, tampering rates, and the number of times an engine is rebuilt. Lifetime cost estimates ranging from \$3.20-\$31.00 per pound, have been suggested.

As discussed in Chapter III, diesel engine exhaust contains a number of potentially toxic compounds. The effect of traps on emissions of toxic or potentially toxic compounds depends on the type of trap used. Uncatalyzed traps are expected to have little effect on HC emissions and, in general, a minimal impact on emissions of lower molecular weight toxic compounds such as benzene, styrene, xylenes and 1,3-butadiene. Their effect on PAH has been shown to be highly variable with conversion efficiencies ranging from 5 to 90 percent reported. However, emissions of nitrated and oxygenated PAH (these particular types of PAH are considered to be more mutagenic than their precursors) have been shown to increase when uncatalyzed traps are used. This is thought to be due to the increased period of time PAH spend in contact with NO_x and oxygen in the exhaust stream. It is unclear if there is a similar increase in emissions of lower molecular weight oxygenates and nitro-compounds. In contrast, traps using noble metal catalysts are expected to substantially reduce emissions of all of the compounds discussed above although, increases in formaldehyde and acetaldehyde have been observed with some catalytic traps. HC conversion efficiencies of up to

75 percent have been reported for catalyzed traps. Because of the large excess of oxygen present in diesel exhaust, catalytic NO_x reduction is not possible and traps have little effect on NO_x emissions. Since traps have the potential to make substantial reductions in emissions of both PM and toxic or potentially toxic compounds, considerable effort to overcome the problems discussed above is warranted.

B. INSPECTION AND MAINTENANCE

Diesel motor vehicles have not been included in the inspection and maintenance program for gasoline-fueled vehicles. An inspection and maintenance program would not achieve a high level of benefits from older vehicles that are not subject to the more stingent limits now being implemented as described in Chapter II. In addition, because many heavy-duty diesel vehicles operating in California are registered, or "base-plated" in other states, the implementation of a diesel vehicle inspection and maintenance program would have to be different than the present "smog-check" program. The staff is now evaluating an inspection and maintenance program for diesel vehicles, the appropriate elements of such a program, and how an inspection and maintenance program could most effectively be implemented.

C. SMOKING VEHICLE INSPECTION

A bill currently being considered by the California Legislature (SB 1997, Presley) would require the ARB to develop a test procedure for roadside inspections to detect excessive smoke emissions from heavy-duty diesel vehicles, and to prohibit the use of heavy-duty vehicles that have excessive smoke emissions.

The ARB staff is investigating test methods and the kind of regulatory program that would be most effective in reducing excesive smoke emissions from heavy-duty diesel vehicles.

VI. DIESEL FUEL SULFUR CONTENT REDUCTION

The sulfur in diesel fuel is responsible for emissions of sulfur dioxide. The sulfur dioxide is converted to particulate sulfate in the atmosphere. The degree of conversion depends on a variety of atmospheric and meteorological conditions.

The evaluation of the effects of diesel fuel sulfur content is a straight forward calculation. Each pound of sulfur in diesel fuel is converted, in the combustion process, to two pounds of sulfur dioxide (except for a very small percentage that is converted to a sulfate species). Thus, for each pound of sulfur removed from diesel fuel, two pounds of sulfur dioxide emissions are reduced.

We evaluated emissions reductions that could be achieved from reduced motor vehicle diesel fuel sulfur content by determining a percentage reduction. Based on a diesel fuel sufur content of 0.28 percent for those areas outside the SCAB and Ventura County, a reduction in diesel fuel sulfur content to 0.05 percent, or 500 parts per million (ppm), would reduce sulfur dioxide emissions by 82 percent. In evaluating reductions of sulfur dioxide emissions that could be achieved from reducing the sulfur content of motor vehicle diesel fuel, as described in the succeeding chapters of this report, we reduced the emission inventory for the areas outside the South Coast Air Basin and Ventura County by 82 percent.

VII. HISTORICAL DATA ON FUEL EFFECTS ON EMISSIONS

A. CHEVRON STUDY AND ANALYSIS

In 1984, investigators at Chevron Research completed a series of tests on a Cummins heavy-duty diesel engine.[1/] The test program evaluated the effects of fuel quality on the engine's emissions using a series of steady-state tests at various loads and engine speeds. The Chevron Research evaluation of the test data provided a linear regression equation that related particulate matter emissions to three fuel variables - the sulfur content, the aromatic hydrocarbon content, and the 90 percent boiling temperature. Chevron Research's regression equation is:

$$PM = 0.00262 \times \%A + 0.00027 \times T90 + 0.354 \times \%S$$

PM = particulate matter emissions in grams per brake horsepower-hour

%A = percent aromatic hydrocarbon

T90 = 90 percent boiling temperature

%S = percent sulfur

Table 6 shows values for particulate matter emissions when the Chevron Research correlation is evaluated using various levels of aromatic hydrocarbon and sulfur contents. Chevron Research's evaluation showed a major role played by the sulfur content in emissions of particulate matter. However, the baseline emissions were low as a result of using steady-state

Table 6

Results of Chevron Research Fuel Effects Tests

Particulate Matter Emissions
(Grams per Brake Horsepower - Hour)

Fuel Specification Scenario	Absolute	Difference from Baseline	Percent Change from Baseline
Baseline	0.342	N/A	N/A
0.05% Sulfur, 31% Aromatics	0.261	0.081	23.8%
0.05% Sulfur, 20% Aromatics	0.232	0.110	32.2%
0.05% Sulfur, 15% Aromatics	0.219	0.123	36.0%
0.05% Sulfur, 10% Aromatics	0.206	0.136	39.9%

Baseline Fuel : Aromatic Hydrocarbon Content = 31 percent
90 Percent Boiling Temperature = 600 degrees F
Sulfur Content = 0.28 Percent

All Fuel Qualities Shown at Constant 90% Boiling Temperature of 600 degrees F.

Source: ARB staff analysis of Chevron Research data.

test cycles. The aromatic hydrocarbon content is also a significant factor in Chevron research's predictive equation.

B. CATERPILLAR/MOBIL STUDY AND ANALYSIS

In 1986, the results of a joint study conducted by Caterpillar Tractor Company and Mobil Oil Corporation on diesel fuel quality effects on emissions was published as a Society of Automotive Engineers (SAE) paper.[2/] The Caterpillar/Mobil study evaluated emissions using both transient and steady-state test cycles. Although regression equations were not developed for emissions versus fuel properties, the Caterpillar/Mobil tests indicated that, under transient cycle test conditions, a reduction in the aromatic hydrocarbon content of diesel fuel results in significant reductions of emissions of both particulate matter and NO_x.

Three different aromatic hydrocarbon contents of diesel fuels were part of the fuel matrix selected by the Caterpillar/Mobil investigators. The aromatic hydrocarbon contents evaluated were 20 percent, 35 percent, and 50 percent. Using the data presented in the Caterpillar/Mobil SAE paper, and extrapolating the aromatic hydrocarbon emission data to lower values than used in the Caterpillar/Mobil study, the staff estimates that a reduction of the aromatic hydrocarbon content of motor vehicle diesel fuel from current levels to 10 percent by volume would result in nearly 50 percent reductions of particulate matter emissions.

VIII. CRC TEST PROGRAM

A. PROGRAM DESCRIPTION

The Coordinating Research Council (CRC) is sponsoring a program to investigate the effects of diesel fuel properties on heavy-duty diesel exhaust emissions. This program is being conducted by the Southwest Research Institute (SwRI) and involves emission tests on three heavy-duty diesel engines using nine different diesel fuels. The nine fuels have different aromatic hydrocarbon content by FIAQ analysis, sulfur content, and volatility characteristics. The ARB participated in this program by sponsoring additional tests for two of the heavy-duty diesel engines. Table 7 shows the average properties of the nine fuels used by SwRI in this program.

The Cummins-NTCC 400 engine was selected as an engine meeting the 1988 California emissions standards. The DDAD-60-11-315 engine was selected and modified to approach the 1991 California and federal emission standards. In addition to the two engines tested, SwRI is currently testing a third heavy-duty diesel engine, a Navistar NIC 7.3-185. The results of tests from this engine are expected to be available by the end of 1988. Descriptions of the engines for which tests have been completed are presented in Table 8.

Table 7

Average Values of Properties of Fuels
Used in the CRC Test Program

Fuel Number	Aromatic Hydrocarbon Content (Vol. %)	Sulfur Content (Mass %)	90% BP °F
1	17	0.302	549
2	44	0.297	558
3	47	0.299	632
4	19	0.291	636
5	34	0.286	602
6	34	0.051	602
7	34	0.164	602
8*	11	0.040	602
9*	43	0.057	605

Source: Coordinating Research Council

*Fuels used for ARB sponsored tests.

Table 8

Descriptions of Engines Tested by CRC

Engine Type	Engine Characteristics
Cummins NTCC400	Six-cylinder, 14 liter displacement, in-line, direct-injection, turbocharged, intercooled, rated power 400 hp at 2100 rpm, fuel consumption 153 lb/hr.
Detroit Diesel DDAD 60-11-315	Six-cylinder, 11 liter displacement in-line, direct-injection, turbocharged, intercooled, rated power 315 hp at 1800 rpm, fuel consumption 105 lb/hr.
Navistar NIC 7.3-185	Eight cylinder, 7.3 liter displacement, V-configuration, indirect injection, naturally aspirated, nominal rated power 185 hp at 3300 rpm, fuel consumption 85.6 lb/hr.

Emission tests for this program are conducted by using two transient and three steady-state operating modes following EPA standard test procedures. The two transient tests conducted are the hot-start and the cold-start conditions. The three steady-state conditions are conducted with intermediate speed and 25 percent load (S1), rated speed with 25 percent load (S2), and rated speed with 75 percent load (S3). The emission species that are being evaluated include total particulate matter (PM), total hydrocarbon (HC), oxides of nitrogen (NO_x), carbon monoxide (CO), soluble organic fractions, sulfates, and benzene. As of the date of writing of this report, test series on the Cummins-400 and DDAD-60 diesel engines have been completed.

B. ARB DATA ANALYSIS AND METHODS

The CRC steering committee for this project (VE-1 committee) agreed to release to the ARB, prior to the completion of the study the emissions test results for the two engines tested to date with the understanding that the ARB staff would perform its own analyses and accept responsibility for the results and the conclusions reached. Analysis of data from the program is being conducted by Southwest Research Institute and will be made available in a report to be published in the first quarter of 1989.

The ARB staff analyzed the test results separately for each engine and for each engine operating mode. We used the Statistical Analysis System (SAS) regression procedure (REG) computer programs. The REG procedure fits least-squares estimates to linear regression models. The procedure was used to perform single and multiple variable linear regression analyses of aromatic hydrocarbon content, sulfur content, and 90 percent boiling temperature against total particulate matter, hydrocarbons, and NO_x emissions. Statistical F-tests were performed to evaluate how well the model accounts for the dependent variable(s) behavior and Student's t-statistics were used to characterize the independent variable contributing to the regression model. Detailed results of our analyses of the CRC data are included in Appendix C.

The VE-1 Committee reviewed our analysis and provided comments which are presented in Appendix D. Based on the VE-1 committee's comments, the ARB staff revised the regression equation for the Cummins engine and for particulate matter to incorporate sulfur as on independent variable in addition to FIA aromatic content although it is only significant at the 90 percent level of significance.

The regression equation developed from this analysis has the form:

$$\text{Emissions} = A + [B \times (\text{Aromatics})] + [C \times (\text{Sulfur})]$$

where

Emissions = Predicted emissions in grams per brake horsepower-hour

Aromatics = Volume percent aromatic hydrocarbons by the FIA method

Sulfur = Sulfur content, fraction by weight

The coefficients A, B, and C together with significance statistics, are shown in Table 9 for the data from the Cummins and the DDAD engines.

Table 9 shows that based on the data from Cummins and DDAD engine, for the emissions and test cycles shown, the aromatic hydrocarbon content and the sulfur content are significant at the 0.0001 level of significance. Values for R-squared show that for the cold start particulate emissions, 61 to 63 percent of the variation can be explained by the aromatic hydrocarbon and the sulfur content as the independent variables. For hot start emissions, 62 to 78 percent of the emission variability is explained by the aromatic hydrocarbon content variable.

Table 9 also shows that based on the data from the DDAD and Cummins engines, for NOx emissions, only the aromatic hydrocarbon content is significant at the 0.0001 level. The aromatic hydrocarbon content explains 56 percent of the variability in cold start NO_x emissions and 62 to 75 percent of the variability in the hot start NO_x emissions.

Table 9

Coefficients for Independent Variables for Cummins and DDAD Engines as in Equation I, pg. 42

Dependent Variable	Independent Variable Coefficients			Analysis of Variance			
	A	B	C	R-Square	Degrees of Freedom	F-Value	Prob > F
Cummins Engine							
PMCS	0.4119	4.93×10^{-3}	0.1822	0.6366	25	32.889	0.0001
PMHS	0.3609	3.76×10^{-3}	0.0695	0.8032	28	96.989	0.0001
NOxCS	3.9118	11.89×10^{-3}	0	0.5610	25	30.674	0.0001
NOxHS	4.2826	12.79×10^{-3}	0	0.6278	28	45.539	0.0001
DDAD Engine							
PMCS	0.2138	215.98×10^{-5}	0.1493	0.6165	30	22.505	0.0001
PMHS	0.1781	97.17×10^{-5}	0.3211	0.7324	30	38.317	0.0001
NOxCS	3.9879	30.59×10^{-3}	0	0.5632	30	37.398	0.0001
NOxHS	3.8496	27.89×10^{-3}	0	0.7581	30	90.894	0.0001

Notes:

PMCS = Particulate Matter Transient Cold Start

PMHS = Particulate Matter Transient Hot Start

NOxCS = NOx Transient Cold Start

NOxCS = NOx Transient Hot Start

B. APPLICATION OF CORRELATIONS

In evaluating the emission reductions that could be achieved by changes to diesel fuel specifications, the staff used the results of the CRC tests that are now available. We believe that this is appropriate for several reasons. First, the CRC test program provides the most extensive data base available. Second, the emission reductions shown for reduced aromatic hydrocarbon content using the regression equations that we have developed are less than the emission reductions shown for the only other fuel quality - emissions evaluation conducted using transient cycle conditions (Caterpillar/Mobil test program). Choosing the lower value for emissions reductions is a conservative approach. Finally, the CRC data analysis shows the fuel effects on emissions from current and future-prototype engines that provides a greater degree of confidence when estimating emission reductions that can be achieved in the future.

To use the data from the CRC study in evaluating the effects of reduced aromatic hydrocarbon content on emissions, the staff weighted the emission reduction effects in the four regression equations such that the hot start transient test is weighted by a factor of 6/7 and the cold start transient test is weighted by a factor of 1/7. This weighting is consistent with the EPA's certification procedure. The weightings and the prediction equations from Table 9 were then used to determine the values for emissions of particulate matter and NO_x at various aromatic hydrocarbon contents as shown in Table 10.

To estimate emissions in grams per horsepower-hour for PM and NO_x using the preditive equations developed from the CRC data, it was necessary to calculate separate emissions for the SCAB and the rest of the state. The diesel fuel used in the SCAB is assumed to have a sulfur content of 0.05 percent by weight. The diesel fuel used in other areas of the state is assumed to have a sulfur content of 0.28 percent by weight. The estimates shown in Table 11 are based on a diesel fuel sulfur content of 0.28 percent by weight for the SCAB and of 0.05 percent for other areas of the state and aromatic hydrocarbon contents of 20, 15, and 10 percent.

Using the data from Table 10, we developed Table 11. Table 11 shows the percent emission reductions for each fuel quality scenario for each engine type. The table shows a significant difference in particulate matter and NOx emissions reductions between the Cummins and the DDAD engines. For example, for particulate matter emissions with an aromatic hydrocarbon content reduction from the baseline to 10 percent, the Cummins engine shows a 17 to 20 percent reduction versus a 10 to 31 percent (depending on initial sulfur content) for the DDAD and the CUmmins engines. The fact that the values for the DDAD engine show a difference in reductions for the SCAB (10-17 percent

Table 10

Emissions of Particulate Matter and NOx for the Cummins and DDAD Engines

	Emissions Grams per Horsepower-Hour			
Fuel Aromatic Hydrocarbon Content, % by Volume:	31%	20%	15%	10%
Fuel Sulfur Content, % by Weight:	*	0.05%	0.05%	0.05%
Cummins Engine				
SCAB				
PM	0.4943	0.4511	0.4314	0.4118
NOx	4.6222	4.4829	4.4196	4.3562
Other Areas				
PM	0.5140	0.4511	0.4314	0.4118
NOx	4.6222	4.4829	4.4196	4.3562
DDAD Engine				
SCAB				
PM	0.2334	0.2209	0.2151	0.2094
NOx	4.7459	4.4349	4.2935	4.1521
Other Areas				
PM	0.3016	0.2209	0.2151	0.2094
NOx	4.7459	4.4349	4.2935	4.1521

* The baseline sulfur content for areas outside the SCAB and Ventura County is 0.28 percent, and the baseline sulfur content for the SCAB and Ventura County is 0.05 percent.

Source: ARB/SSD analysis of CRC data.

Table 11

Percent Emissions Reduction for NOx and Particulate Matter for Cummins and DDAD Engine*

Fuel Quality Scenario:	Percent Emissions Reduction 20% Aromatics 0.05% Sulfur	15% Aromatics 0.05% Sulfur	10% Aromatics 0.05% Sulfur
Cummins Engine			
SCAB			
PM	9	13	17
NOx	3	4	6
Other Areas			
PM	12	16	20
NOx	3	4	6
DDAD Engine			
SCAB			
PM	5	8	10
NOx	7	10	13
Other Areas			
PM	27	29	31
NOx	7	10	13

* The predictive equations for PM emissions included sulfur variables. Percent emission reductions are based an uncontrolled fuel containing 31 percent aromatic hydrocarbons, with sulfur contents of 0.05 percent in the South Coast Air Basin and Ventura County, and 0.28 percent elsewhere in the state.

Source: ARB/SSD analysis of CRC data.

reduction) compared to other areas in the state (20-31 percent) relects the influence of the sulfur content for the baseline case. The baseline sulfur content for the SCAB diesel fuel is 0.05 percent for the SCAB and 0.28 percent for the rest of the state.

D. MUTAGENICITY STUDY

A number of exhaust particulate samples from the CRC Cummins engine tests were collected by SWRI and the extracts were sent to Dr. Ronald Rasmussen of U.C. Irvine to perform Ames mutagenicity tests. The Ames tests were conducted with ten samples from the hot-start transient tests, ten samples from the cold-start transient tests, and ten samples from steady-state tests. Dr. Rasmussen reported the results of the Ames tests in a report titled "Genotoxicity of Diesel Exhaust Particles and Vapors Collected from Engines with and without Particulate Trap Oxidizers," June 30, 1988.[3/]

The results of Dr. Rasmussen's tests show that in "nearly every case increased aromatic content of the fuel was positively associated with mutagenic activity, although in some cases the level of statistical significance was marginal." Differences of up to ten-fold or more in mutagenic activity were seen between fuels having either 10 or 41 percent aromatic hydrocarbon content. Other researchers have reported two to five-fold lower mutagenic activity in exhaust particles when using 17 percent aromatic hydrocarbon fuel versus 36 percent aromatic fuel in heavy duty diesel engines.[4/]

IX. EMISSIONS REDUCTIONS

To evaluate the emissions reductions that could be achieved by changes to motor vehicle diesel fuel quality, we estimated the 1995 and 2010 projected baseline emissions inventory by using the EMFAC-7 methodology for the on-road vehicle emissions inventory and the ARB's area source emission inventory methodology for the off-road vehicle emissions inventory. We then estimated the 1995 and 2010 emission inventories for each proposed regulatory scenario. In the development of the emission inventory estimates for the years 1995, 2000, 2005, and 2010 and for each regulatory scenario, we used the EMFAC-7 methodology and we also incorporated the following assumptions:

(a) On-road vehicles.

First, as previously mentioned, we assumed that for 1991-1994 model years HDD engine manufacturers will comply with the 1991 emission standards by engine modifications only and therefore the tampering and malmaintenance impact on emissions for the 1991-1994 model year engines will be zero. Second, we assumed that the pre-1990 HDD engines are represented by the Cummins CRC engine and therefore, the emissions reductions impact of the various regulatory scenarios will be as shown for the Cummins engine correlations shown in Table 9. For the post-1990 engines we have assumed that the DDAD engine represents those engines and therefore, the emissions reductions achievable by the various regulatory scenarios are the same as for the DDAD engine correlations shown in Table 9. Third, we assumed that the percent reduction as estimated by the CRC correlation for both engine types are appropriate for the trap-equipped post-1994 heavy-duty vehicles.

(b) Off-road vehicles.

We have assumed that for all off-road vehicles the emission impacts of the proposed regulatory scenarios will be represented by the Cummins engine correlation as shown in Table 9.

The differences between the baseline inventory and the inventory under the proposed regulatory scenarios yield the emission reductions in tons per day. The statewide and SCAB emission reductions that could be achieved based on the 1995 and 2010 emissions inventories are shown in Tables 12 and 13.

The potential statewide PM emissions reductions in 1995, as shown in the Table 12, range from 8.7 tons per day for diesel fuel containing 20 percent aromatic hydrocarbons and 0.05 percent sulfur, to about 14 tons per day for diesel fuel containing 10 percent aromatic hydrocarbons and 0.05 percent sulfur. For the same levels of aromatic hydrocarbons and sulfur for the DDAD engine, the emission reduction values are 1.2 tons per day and 2.4 tons per day.

The potential statewide NO_x reductions in 1995, as shown in Table 12, range from 27 tons per day for diesel fuel containing 20 percent aromatics and 0.05 percent sulfur to 53 tons per day for diesel fuel containing 10 percent aromatic hydrocarbons and 0.05 percent sulfur.

Table 12
Emissions Reduction
for Each Fuel Specification Scenario

	1995 Emissions Reduction Tons/Day			
Fuel Specification Scenario:	31% Aromatics 0.05% Sulfur	20% Aromatics 0.05% Sulfur	15% Aromatics 0.05% Sulfur	10% Aromatics 0.05% Sulfur
Statewide				
SO2	80	80	80	80
PM	4	9	11	14
NOx	0	27	40	53
South Coast Air Basin				
SO2	0	0	0	0
PM	0	1.2	1.8	2.4
NOx	0	7	10	13

Source: ARB/SSD

Table 13
Emissions Reduction
for Each Fuel Specification Scenario

Fuel Specification Scenario:	2010 Emissions Reduction Tons/Day			
	31% Aromatics 0.05% Sulfur	20% Aromatics 0.05% Sulfur	15% Aromatics 0.05% Sulfur	10% Aromatics 0.05% Sulfur
Statewide				
SO2	96	96	96	96
PM	5	8	10	11
NOx	0	44	66	87
South Coast Air Basin				
SO2	0	0	0	0
PM	0	0.6	0.9	1.2
NOx	0	11	16	21

Source: ARB/SSD

The foregoing emission reduction analysis does not consider reductions in secondary particulate matter that is formed in the atmosphere from SO_2 or NO_x emissions from diesel engines. It has been reported that about 0.3 pounds of ammonium nitrate particulate matter is formed for each pound of NO_x in the atmosphere, and that 25 to 75 percent of SO_2 emitted to the atmosphere is converted to particulate ammonium sulfate.[5/] Inclusion of secondary particulate matter would increase the particulate matter reductions that could be achieved from changes to diesel fuel quality.

In addition to the methodology outlined above, we evaluated the emission reductions that culd be achieved when other test data are used to estimate fuel effects on emission reductions. To estimate fuel composition effects on new technology vehicle emissions, we assumed that the DDAD engine tests by CRC represented future (post 1990) engine technology. To estimate fuel composition effects on current technology engines we used all of the other heavy-duty diesel engine test data available. The results of this approach compared to the CRC-only approach is shown below and in Figures 9 and 10.

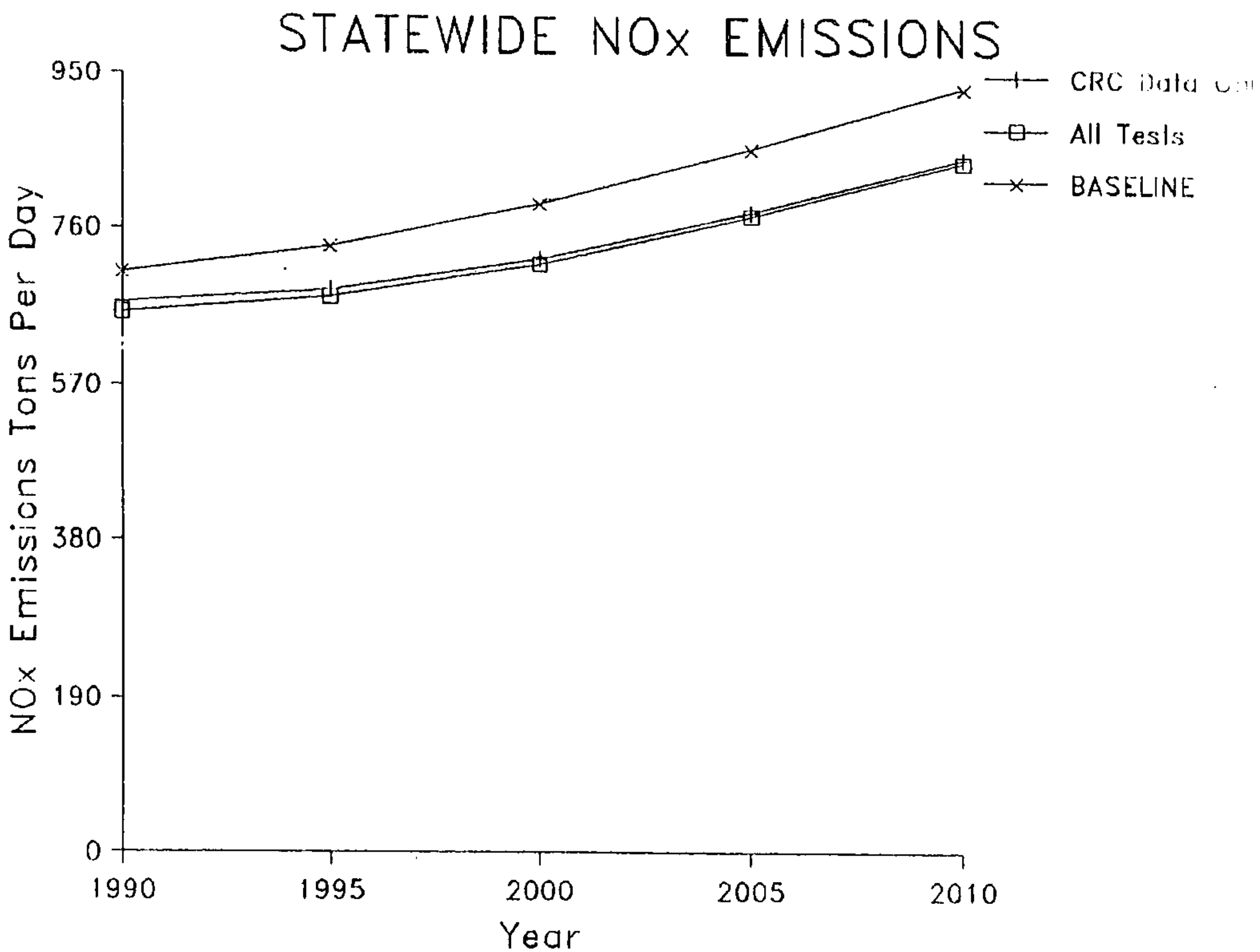
Emissions Reductions for Reducing Diesel Fuel Sulfur Content to 0.05 Percent and Aromatic Hydrocarbon Content to 10 Percent

	Emission Reductions, Tons Per Day		
	<u>SO_2</u>	<u>PM</u>	<u>NO_x</u>
<u>1995</u>			
Using all data	80	22	61
Using only CRC data	80	14	53
<u>2010</u>			
Using all data	96	16	86
Using only CRC data	96	11	91

The emission reductions for our proposed limits on sulfur and aromatic hydrocarbon content would be less if we used only the CRC engine test data rather than all available data. Because we believe that the CRC data are the most complete data available, and because using the Cummins engine to represent current technology engines provides conservative emissions reduction estimates, we used only the CRC data in evaluating emission reductions.

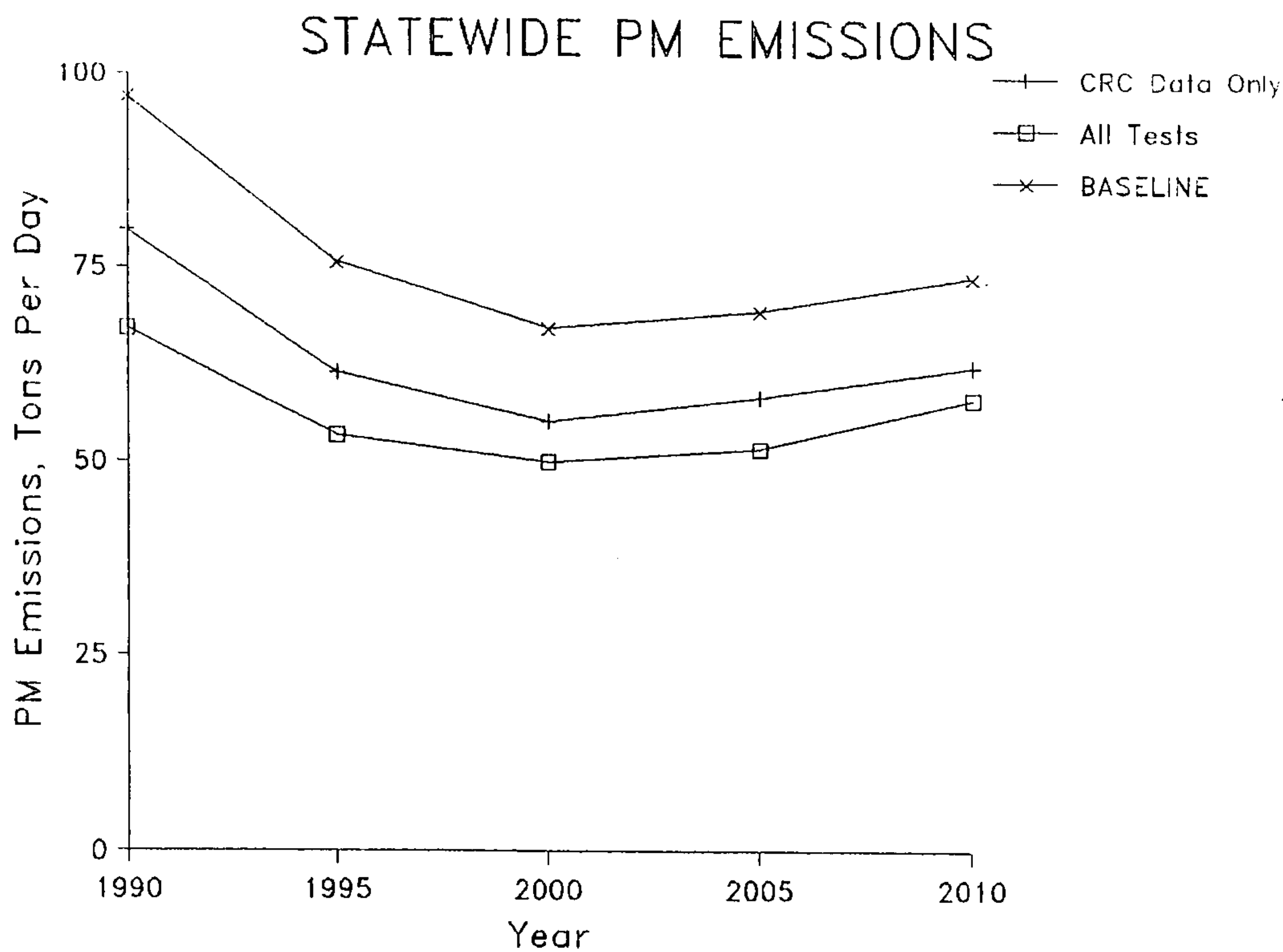
Throughout the remainder of this report, emission reductions and cost-effectiveness values for which emissions reductions are part of the calculations will be based on our emission reduction data as shown in Tables 12 and 13.

Figure 9



Source: ARB/SSD

Figure 10



Source: ARB/SSD