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HEAVY-DUTY DIESEL VEHICLE INSPECTION AND MAINTENANCE STUDY

FINAL REPORT
VOLUME II

QUANTIFYING THE PROBLEM

Submitted to:

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1.0 INTRODUCTION

In order to protect and improve the quality of its air, the State of California is interested in minimizing pollutant emissions from heavy-duty diesel trucks and buses. Diesel-engined vehicles are major contributors to ambient levels of particulate matter and oxides of nitrogen (NO_x) in urban air. Diesels also emit lesser (but still significant) amounts of unburned hydrocarbons (HC), and a small amount of carbon monoxide (CO). Diesel HC emissions are of special concern, since the hydrocarbon species emitted include polynuclear aromatic compounds, nitro-aromatics, and other toxic, carcinogenic, or mutagenic species. Diesel HC and aldehyde emissions are also responsible for the characteristic diesel odor.

New motor vehicles must meet strict pollutant emission standards before they can be sold. In order to improve the level of emissions control in customer use, however, California and many other states have found it necessary to implement programs of periodic inspection and maintenance (I/M) to check emissions levels and/or the functioning of emissions controls, and require corrective repairs where necessary. California presently has a strong I/M program for light-duty and some heavy-duty gasoline vehicles, and has considered a similar program for light-duty diesels. Heavy-duty vehicles, especially diesels, have traditionally been exempted from I/M requirements, however.

Implementation of I/M programs for diesels has been impeded by the technical difficulty of developing a suitable emissions test, and by uncertainty as to the magnitude of the problem and of the cost-effectiveness of an I/M program for these vehicles. In response to the need for improved control of heavy-duty diesel emissions, however, the California Air Resources Board (ARB) commissioned Radian Corporation to quantify the problem of excess emissions from heavy-duty diesel trucks and buses, to develop preliminary I/M procedures for these vehicles, and to estimate the costs and cost-effectiveness of implementing an I/M program for heavy-duty diesels.

1.1 Outline of the Study

The project was divided into five major tasks, as listed below.

(1) Quantify the problem of excess emissions from heavy-duty diesels due to poor maintenance and/or tampering with emission controls. This task included defining common emissions-related defects, estimating the frequency of defects in the truck population, estimating the emissions consequences of each defect, and combining these estimates with data on truck populations and travel patterns to estimate the impact of excess emissions from heavy-duty diesels on air quality and public offense due to excessive smoke.

(2) Develop and document a periodic inspection procedure and a quick roadside smoke opacity check to identify heavy-duty diesel vehicles having excessive emissions. The periodic inspection procedure was intended to be conceptually similar to the procedures for the present Smog Check Program for light-duty gasoline vehicles. The roadside opacity check procedure was intended as a quick and simple check for excessive emissions which could be applied at a truck weigh station or similar environment.

(3) Estimate the costs and emissions benefits of implementing the procedures developed in Task Two, assuming that the emissions defects identified by the procedure are properly repaired.

(4) Validate the procedures developed in Task Two by applying them to a representative sample of trucks in a blind test.

(5) Prepare a final report documenting the work.

1.2 Outline of the Report

The final report for this project is contained in four volumes, of which this is Volume II. The volume numbers and their titles are as follows:

I. SUMMARY REPORT

II. QUANTIFYING THE PROBLEM

III. DEVELOPMENT AND VALIDATION OF I/M TEST PROCEDURES

IV. I/M PROGRAM DESIGN AND COST-EFFECTIVENESS ANALYSIS

Volume I presents an overview of the other three volumes, and summarizes the major conclusions and recommendations. Volume II, this volume, describes a computer model of heavy-duty diesel emissions developed for this project, and presents the model results for the case with no I/M program. Volume III describes the development and validation of emissions test procedures to identify heavy-duty diesel vehicles which are excess emitters. Volume IV, finally, outlines several possible designs for I/M programs using these procedures, and estimates the resulting emissions reductions and the cost-effectiveness of each, using the model documented in this volume.

1.3 Guide to the Remainder of Volume II

Volume II is divided into ten sections, of which this Introduction is the first. Section Two, following, provides an overview of heavy-duty diesel engines and vehicles which serves as background for the sections which follow. Section Three then discusses the types of malmaintenance and tampering which can lead to excessive emissions.

The next three sections describe a computer model--developed by Radian for this project--of the effects of tampering and malmaintenance on heavy-duty diesel emissions. Section Four presents the structure of the model itself, and the data on truck populations, travel, etc., which go into it. Section Five presents our estimates of the frequency with which each type of emissions-related defect is occurring or would occur (in the absence of an I/M program) in each class of heavy-duty diesel trucks and buses, along with the supporting data for these estimates. Section Six describes the estimated effect of each type of defect on NO_x, HC, and PM emissions and fuel economy.

In the model, the estimates developed in Sections Five and Six are combined to calculate the net change in heavy-duty diesel emission factors and fuel economy as a result of malmaintenance and tampering with emission controls. The results of these calculations are reported in Section Seven. The resulting emission factors are then combined with travel data to estimate the resulting increase in total emissions: statewide and for each critical air-pollution area in the state. These data are presented in Section Eight. Section Nine presents our sensitivity analysis of the results, examining the effects of varying critical assumptions on the final results. Detailed model output and other supporting data are included in a series of appendices.

1.4 Limitations and Caveats

This report describes the structure, input data, and results of a mathematical model of heavy-duty diesel emissions. Neither this model nor any other can produce "Truth"--at best, it can only reflect the consequences of the data and assumptions that go into it. Any mathematical model represents an abstraction and simplification of reality. Whether this abstraction adequately represents reality depends on the uses to which the model results are put. The model was designed to evaluate the impact of tampering and malmaintenance practices on diesel emissions, and we believe that it adequately represents these effects. The user is responsible for assessing its applicability to other types of studies.

No model can be more accurate than its input data. Due to the lack of hard statistical information, it has been necessary to estimate values for many of the critical input data going into this model. These estimates are based on the best data available, supplemented by informed engineering judgement, and we consider them to be both reasonable and somewhat conservative. In the absence of hard statistics, however, they cannot be shown to be "right." The estimated uncertainty in the assumptions (and thus in the results) is discussed at greater length in Section Nine.

2.0 BACKGROUND INFORMATION: HEAVY-DUTY DIESEL VEHICLES AND ENGINES

This Section provides an overview of heavy-duty diesel vehicle classification, diesel engine technology, and diesel emissions control. It is intended to supply background information for those previously unfamiliar with the area, and to establish definitions for the more technical chapters which follow.

2.1 Heavy-Duty Vehicle Characteristics

For regulatory purposes, highway vehicles are divided into two major classes: light-duty vehicles and heavy-duty vehicles. Light-duty vehicles include passenger cars and all trucks having a manufacturer's rated gross vehicle weight (GVW) less than 8,500 pounds. Trucks and buses with a rated GVW of 8,500 pounds or more are classed as heavy-duty vehicles. Light-duty vehicles have been subject to increasingly stringent emission-control regulation over the past two decades. Heavy-duty vehicles have only recently begun to experience a similar level of regulatory interest.

Vehicles classed as "heavy-duty" span an enormous range of sizes and uses. They range from pickups and vans which are basically uprated versions of light-duty vehicles to huge tractors towing multiple trailers rated at 150,000 pounds gross combined weight. One commonly used system for classifying these vehicles was developed by the Motor Vehicle Manufacturer's Association (MVMA). Classification is on the basis of GVW, and ranges from Class 1 (0-6000 lb GVW) to Class 8 (33,001 lb GVW and up). In emissions work, MVMA Class 2 (6001-10,000 lb GVW) is commonly subdivided into Classes 2a (6001-8,500 lb) and 2b (8,501-10,000 lb) to separate vehicles classed as light and heavy-duty by EPA. This classification system is diagrammed in Figure 2-1.

Although it is simple and widely used, the MVMA classification system does not adequately reflect current heavy-duty vehicle classes. Almost no vehicles are produced in MVMA classes 3 and 4, for instance, while class 8

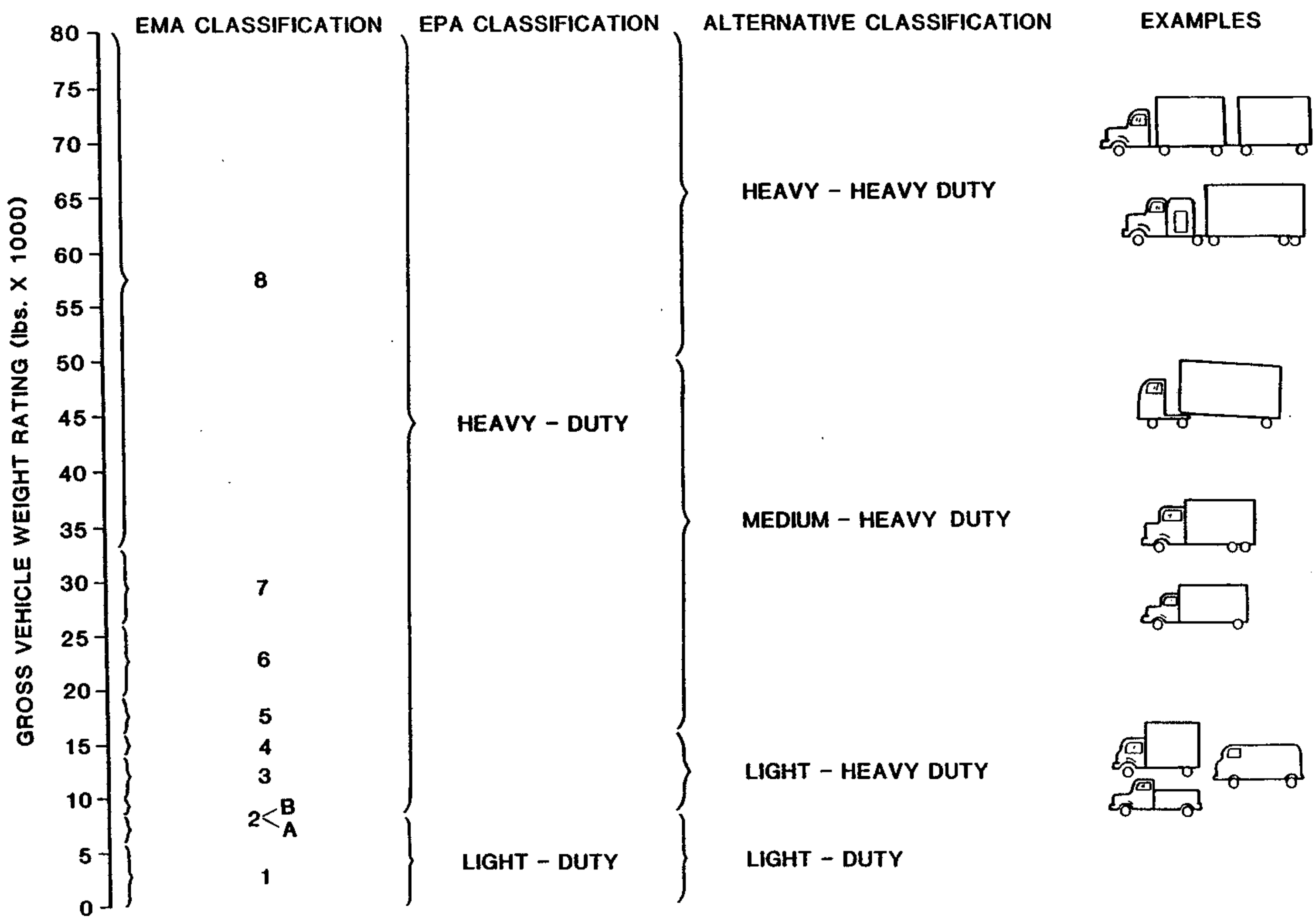


Figure 2-1. Heavy-Duty Vehicle Classification

lumps together many different kinds of heavy trucks, some of which have very different design and usage characteristics. Because of these problems, an alternative classification system--also shown in Figure 2-1--has come into increasing use. In this system, heavy-duty trucks are divided along both size and functional lines into three classes: light-heavy, medium-heavy, and heavy-heavy. Because of their unique ownership and operating characteristics, transit buses are treated separately, as a fourth class.

Light-heavy duty vehicles are mostly large pickups and vans, and specialty vehicles (such as motor homes) built on pickup and van chassis. The engines, production methods, and usage patterns in this class closely resemble those in light-duty vehicles. Most vehicles in this class are still gasoline powered. Diesel engines are commanding an increasing share of the market, however, making this the most rapidly growing class of diesel vehicles.

Medium-heavy duty vehicles include school buses, nearly all single-unit trucks, and light (so-called "city") truck-tractors. These are trucks intended mostly for pick-up and delivery, stop-and-go operation in cities under moderate load. Heavy-heavy duty vehicles, on the other hand, are large, heavy, and very powerful trucks intended primarily for long-distance freight and heavy hauling applications. Virtually all are heavy tractor/trailer or truck/trailer combinations.

Transit buses fall into the same weight and size classification as medium-heavy duty vehicles, but their unique operating patterns and areas of operation result in a disproportionate impact on urban air quality. It has been estimated (Chock et al.,1984) that buses may account for as much as 40 percent of all diesel particulate matter measured in some congested urban areas. Buses have accordingly been singled out for special attention, both by emissions analysts and by EPA regulations.

Industry structure--The U.S. medium-heavy and heavy-heavy truck industry is unique. Unlike the producers of light-duty and light-heavy duty vehicles, the manufacturers of U.S. medium-heavy and heavy-heavy duty trucks are largely custom assemblers of major subassemblies produced by others. A truck purchaser can typically choose among several engine models from two or three different manufacturers. One of these manufacturers may or may not be the same corporation as the truck builder. GMC trucks, for instance, are commonly offered with Cummins and Caterpillar as well as Detroit Diesel engines. Cummins and Caterpillar--the two largest heavy-heavy duty engine builders--produce no trucks; many of the largest heavy-heavy truck builders produce no engines. A similar degree of disaggregation exists for truck transmissions, drive axles, and specialized truck bodies.

2.2 Diesel Engine Technology

Diesel engines used in light-heavy duty vehicles mostly resemble those used in light-duty trucks. Medium-heavy and heavy-heavy duty engines and vehicles (including transit buses) are distinctly different from light-duty engines in technology, durability, and usage patterns. Premium features such as turbocharging, aftercooling, and four-valve cylinder heads--all new in the light-duty market--have been common for some time in heavy-heavy duty engines.

These engines are also built to higher standards of efficiency and durability than light-duty or light-heavy duty engines. Thermal efficiencies exceeding 40 percent (comparable to the best fossil fuel power plants) are common in heavy-heavy engines, and engines in normal service may run from 200,000 to more than 400,000 miles before they are worn out. The costs of these engines reflect these qualities--a medium-heavy duty engine may cost $5,000 to $10,000 or more, and a premium heavy-heavy engine may cost more than $20,000.

In addition to being extremely durable to begin with, many medium-heavy and all heavy-heavy engines are designed to be easily overhauled and rebuilt. Removable cylinder liners are standard on heavy-heavy engines, for instance. With proper care, these engines can be rebuilt and reused indefinitely, and it is not at all unusual for a heavy-heavy truck engine to accumulate three rebuilds and more than a million miles during its lifetime. This has profound implications for in-use emissions, since (depending on the practices followed) rebuilding the engine may significantly change its emissions characteristics.

Combustion Systems--Diesel engines can be divided into two groups on the basis of the location where fuel injection and combustion take place. In an indirect-injection engine, fuel is injected into a separate "prechamber," where it mixes and partly burns before jetting into the main combustion chamber above the piston. In the more common direct-injection engine, fuel is injected directly into a combustion chamber hollowed out of the top of the piston. Fuel-air mixing in the direct-injection engine is limited by the fuel injection pressure and any motion imparted to the air in the chamber as it entered.

In the indirect-injection engine, much of the fuel-air mixing is due to the air swirl induced in the prechamber as air is forced into it during compression, and to the turbulence induced by the expansion out of the prechamber during combustion. These engines typically have lower emissions and better high-speed performance than direct-injected engines, and can use cheaper fuel-injection systems. The extra heat and frictional losses due to the prechamber result in a 5-10 percent reduction in fuel efficiency, however. For these reasons, all light-duty and most light-heavy duty diesels in the U.S. use indirect-injection engines, but all medium-heavy and heavy-heavy engines are direct-injected.

Fuel Injection Systems--The fuel injection system in a diesel engine includes the machinery by which the fuel is transferred from the fuel tank to the engine, then injected into the cylinders at the right time for optimal combustion, and in the correct amount to provide the desired power output. The quality and timing of fuel injection dramatically affect the engine's power, fuel economy, and emissions characteristics, so that the fuel injection system is one of the most important components of the engine.

The fuel injection system normally consists of a low pressure pump to transfer fuel from the tank to the system, one or more high-pressure fuel pumps to create the pressure pulses that actually send the fuel into the cylinder, the injection nozzles through which fuel is injected into the cylinder, and a governor and fuel metering system. These determine how much fuel is to be injected on each stroke, and thus the power output of the engine.

Three generic types of fuel injection systems are in common use. These are:

1. Systems with distributor-type fuel pumps, in which a single pumping element is mechanically switched to connect to high-pressure fuel lines leading to each cylinder in turn;

2. Systems with unitary fuel pumps having one pumping element per cylinder, connected to the injection nozzle by high-pressure fuel lines (often called "in-line pumps"); and

3. Systems using unit injectors, in which the individual pumping element for each cylinder is combined in the same unit with the injection nozzle, eliminating the high-pressure lines.

Distributor pumps are relatively inexpensive, but they are limited in the injection pressures they can achieve. For this reason, they are used mostly in indirect-injection engines. In-line pumps are capable of much higher injection pressures. Mack, Navistar, Caterpillar, Ford and nearly all European and Japanese diesel manufacturers use in-line pumps. Unit injector systems are capable of the highest injection pressures (exceeding 25,000 PSI).

They are used in Cummins and Detroit Diesel-Allison (DDA) truck engines, and in many larger diesels.

Distributor and in-line pumps are typically driven by a special driveshaft from the engine timing gears. This allows the injection timing to be varied by rotating the pump with respect to its driveshaft, using a sliding helical spline. The pumping elements in unit injector systems are driven by the engine camshaft, in the same way as the intake and exhaust valves. Until recently, injection timing in unit injector systems has been fixed by the system geometry (except for the effects of wear). However, both Cummins and DDA have recently introduced variable injection timing systems for their engines. The Cummins system operates by moving the injector cam followers slightly with respect to the camshaft. The DDA system involves full electronic control of injection start and stop, using a solenoid valve.

2.3 Diesel Emissions Fundamentals

Diesel engines emit significant quantities of oxides of nitrogen (NO_x), sulfur oxides (SO_x), particulate matter (PM), and unburned hydrocarbons (HC). The NO_x, HC, and most of the PM emissions from diesels are formed during the combustion process, and can be controlled by appropriate modifications to that process. The sulfur oxides, in contrast, are derived directly from sulfur in the fuel, and the only feasible control technology is to reduce fuel sulfur content. Most SO_x is emitted as gaseous SO_2, but a small fraction (typically 2-3 percent) occurs as particulate sulfates in the exhaust.

Diesel particulate matter consists mostly of three components: soot formed during combustion, heavy hydrocarbons condensed or adsorbed on the soot, and particulate sulfates. Soot is typically 40-80 percent of the total, with most of the rest being heavy hydrocarbons. These are referred to as the soluble organic fraction or SOF. A significant fraction of the SOF is derived from the lubricating oil, but most is either fuel-derived or formed during combustion, possibly by the same processes that produce soot. Sulfates are typically 5-10 percent of the particulate mass, depending on the operating conditions and the fuel's sulfur content.

The particulate SOF and gaseous hydrocarbons from diesel engines include many known or suspected carcinogens and other toxic air contaminants. These include polynuclear aromatic compounds (PNA) and nitroaromatics, formaldehyde and other oxygenated hydrocarbons. These last are also responsible for much of the characteristic diesel odor.

NO_x/Particulate Tradeoff--Diesel particulate and NO_x emissions result from the fundamental nature of the combustion process, making them especially difficult to control. All diesel engines rely on heterogeneous combustion, as opposed to spark-ignition engines, which use a more-or-less homogeneous charge. During the compression stroke, a diesel engine compresses only air. Fuel is injected into the combustion chamber in liquid form near the top of the compression stroke. The quantity of fuel injected with each stroke is determined by the engine power output required. After a brief period known as the ignition delay, the fuel is ignited by the hot air and burns. In the premixed burning phase, the fuel/air mixture formed during the ignition delay period burns rapidly. The subsequent rate of burning is controlled by the rate of mixing between the remaining fuel and air, with combustion always occurring at the interface between the two. This "diffusion burning" stage accounts for most of the fuel burned, except under very light loads.

The fact that fuel and air must mix before burning means that a substantial amount of excess air is needed to ensure complete combustion of the fuel within the limited time allowed by the power stroke. Diesel engines, therefore, operate at overall air-fuel ratios which are considerably lean of stoichiometric. The air-fuel ratio during a given stroke is determined by the engine power requirements, which govern the amount of fuel injected (the amount of air is more or less constant). The minimum air-fuel ratio for complete combustion is about 21, corresponding to about 50 percent excess air. This ratio is known as the smoke limit, since smoke increases dramatically at ratios lower than this. The smoke limit establishes the maximum amount of fuel that can be burned per stroke, and thus the maximum power output of the engine.

The rate of NO formation in diesels is an exponential function of the flame temperature. In diffusion burning, flame temperature depends only on the heating value of the fuel, the heat capacity of the reaction products and any inert gases present, and the starting temperature of the initial mixture. Most NO_x is formed during combustion near tóp-dead-center (TDC), since this is when the temperature of the charge is greatest. Actions which reduce the flame temperature during combustion also reduce NO_x emissions. These actions include delaying combustion past TDC, reducing the compression ratio, cooling the air charge, and exhaust gas recirculation--which dilutes the reactants with additional inert gases. Since combustion always occurs under near-stoichiometric conditions, reducing the flame temperature by "lean-burn" techniques, as in spark-ignition engines, is impossible.

Most of the soot formed during diesel combustion is subsequently burned during the later portions of the expansion stroke. Soot oxidation is much slower than soot formation, however. The amount of soot oxidized is heavily dependent on the availability of high temperatures and adequate oxygen during the later stages of combustion. Actions which reduce the availability of oxygen (such as EGR, or operation beyond the smoke limit), or which reduce the time available for soot oxidation (such as retarding the combustion timing) tend to increase soot emissions.

There is thus an inherent conflict between some of the most powerful diesel NO_x control techniques and particulate emissions. This is the basis for the much-discussed "tradeoff" relationship between diesel NO_x and particulate emissions. This "tradeoff" is not absolute--other NO_x control techniques such as charge cooling (which increases the amount of oxygen in the cylinder--have neutral or even beneficial effects on particulate emissions.

Visible Smoke--The exhaust plume from a properly adjusted diesel engine is normally invisible (less than 5 percent opacity) under most conditions. Visible smoke emissions from heavy-duty diesels are typically due to operating at air-fuel ratios at or below the smoke limit, or to poor fuel-air mixing in the cylinder. Poor mixing is normally the result of clogged or worn fuel injection nozzles, but may also occur during "lug-down"--high-torque operation at low engine speeds. Low air-fuel ratios may occur as a result of a plugged air filter, defective turbocharger, or other problems, as discussed in Section Three. Marginal air-fuel ratios also occur in full-power operation of naturally-aspirated engines, resulting in some visible smoke under these conditions.

In turbocharged engines, low air-fuel ratios can also occur during transient acceleration, since the inertia of the turbocharger rotor means that the air supply during the first few seconds of a full-power acceleration is less than the air supply in steady-state operation. To overcome this problem, turbocharged engines in highway trucks incorporate an acceleration smoke limiter, which limits the fuel flow to the engine until the turbocharger has time to respond. The setting on this device must compromise between acceleration performance and low smoke emissions; this compromise normally permits some visible smoke.

2.4 Emission Regulations

As might be imagined, the large variety of truck configurations resulting from the disaggregate structure of the industry poses problems for regulators. Due to the variety of heavy-duty truck models, equipment options, and duty cycles, it would be impractical to specify heavy-duty emissions limits in terms of pollution per unit of distance travelled (e.g. grams/mile), as is done with light-duty vehicles. For this reason, heavy-duty emissions regulations are written to apply to the engine, rather than to the vehicle. These regulations are expressed in terms of units of pollution per unit of work done by the engine, as measured over a specified test cycle on an engine dynamometer. The specific units of the U.S. regulations are grams of pollutant per brake horsepower-hour (g/BHP-hr). Heavy-duty diesel engines are also subject to a separate regulation governing maximum smoke opacity.

Table 2-1 shows the applicable California and Federal emissions limits established for heavy-duty engines of various model years. Currently, only gaseous emissions and diesel smoke opacity are regulated, but new Federal and California limits on diesel particulate emissions are scheduled for 1988.

Test procedures--The test cycles and other procedures under which emissions are measured are as important as the numerical emissions limits shown in Table 2-1. Until recently, gaseous emissions were measured on the "13-mode" cycle, which involved operating the engine in steady state at nine different power and speed settings, with intervening periods of idle operation. For diesel engines, this was superseded by the current Federal Heavy-Duty Transient Test cycle, in which engine speed and load are continually varied according to a fixed schedule to simulate a typical urban driving pattern. Both cold-start and hot-start versions of the same cycle are run; the final result reported is the weighted average of the two, with the hot-start weighted 6/7 and the cold start weighted 1/7 of the total.

Since diesel HC and particulate emissions can increase dramatically during engine transients and cold starts, the Heavy-Duty Transient test procedure is considered to give measurements more representative of in-use operation than the old 13-mode cycle. This representativeness has been achieved at considerable cost, however. Dynamometer facilities capable of running the new transient procedure are much more expensive and complex than those needed for the 13-mode test, and the productivity (in tests per day) is much lower.

TABLE 2-1. FEDERAL AND CALIFORNIA EMISSIONS REGULATIONS FOR HEAVY-DUTY DIESEL ENGINES

	CO (g/BHP-hr)	HC (g/BHP-hr)	NO_x (g/BHP-hr)	PM (g/BHP-hr)	Test Procedure	Smoke Opacity (Acc/Lug/Peak, %)
Federal						
1974-1978	40		16[a]	NR	13-Mode	20/15/50
1979-1984	25	1.5	10[a]	NR	13-Mode	20/15/50
1985-1987	15.5	1.3	10.7	NR	Transient	20/15/50
1988-1989	15.5	1.3	10.7	0.6	Transient	20/15/50
1990	15.5	1.3	6.0	0.6	Transient	20/15/50
1991-1993	15.5	1.3	5.0	0.25	Transient	20/15/50
1994+	15.5	1.3	5.0	0.1	Transient	20/15/50
California						
1973-1974	40		16[a]	NR	13-Mode	b
1975-1976	30		10[a]	NR	13-Mode	b
1977-1979	25	1.0	7.5	NR	13-Mode	b
1980-1983	25	1.0	6.0[a]	NR	13-Mode	b
1984-1987	15.5	1.3	5.1	NR	Transient	b
1988-1990	15.5	1.3	6.0	0.6	Transient	b
1991-1993	15.5	1.3	5.0	0.25	Transient	b
1994+	15.5	1.3	5.0	0.1	Transient	b
Typical Certification Levels: 1985 Engines						
Federal Engine	2.0	0.7	8.0	0.65[c]	Transient	13/6/21
California Engine	2.0	0.7	5.0	0.80[c]	Transient	15/9/23

NR: Not regulated

[a] Sum of NO_x plus HC emissions
[b] Federal Smoke Standard applied
[c] Not certified, values shown are typical

Diesel smoke opacity is measured in a separate test procedure. This procedure simulates an acceleration from stop, followed by a gear change and continued acceleration, followed by "lugging down" from full engine power to the maximum torque point. This procedure measures only the occurrence of offensively high visible smoke levels in the operating modes most likely to produce them. The correlation between smoke measurements and average particulate mass emissions over the entire test cycle is poor in new engines. (As discussed in Volume III however, there is a good correlation between increased smoke and increased particulate emissions in-use.) Meeting the new Federal and California particulate standards will require major reductions in visible smoke, and should result in much lower smoke levels than those specified in the Federal smoke standards.

Impact of regulations--Of the pre-1988 gaseous emission limits shown in Table 2-1, only the California NO_x limit had much relevance for diesels. As the "typical" emissions values show, diesel engines could easily comply with the HC and CO limits set, and most Federal engines certified to NO_x levels well below the applicable standard of 10.7 g/BHP-hr.

Diesel engine designers faced a significant challenge, however, in the new nationwide particulate standard scheduled for 1988, and the NO_x standards scheduled for 1988 in California, and for 1990 in the rest of the U.S. While existing engines could readily comply with either the 6.0 g/BHP-hr NOx standard or the 0.6 g/BHP-hr particulate standard, the tradeoff relationship between NO_x and particulate emissions required substantial technological advances in order to meet both standards together.

Meeting the 1991 standards of 5.0 g/BHP-hr NO_x and 0.25 g/BHP-hr particulate matter will require the use of still more advanced NO_x controls than those required in 1988, and will require some manufacturers to use exhaust-treatment devices such as catalytic converters or trap-oxidizers to reduce particulate emissions. An even stricter particulate limit of 0.1 g/BHP-hr will apply to buses in 1991, and to all vehicles in 1994. Compliance with this standard, if it can be achieved at all, will probably require an oxidation catalyst as well as a trap-oxidizer and advanced NO_x controls.

Useful life--For 1988 and subsequent years, EPA regulations require that engines must comply with the applicable emission limits over their EPA-defined "full useful lives". Three classes of heavy-duty engines have been defined for the purpose of useful life determination: light-heavy duty, with a specified useful life of 110,000 miles; medium-heavy duty, 185,000 miles; and heavy-heavy duty, 290,000 miles. These engine classifications correspond closely to the vehicle classifications discussed above--light-heavy engines are typically used in light-heavy vehicles, medium-heavy engines in medium-heavy vehicles, and heavy-heavy engines in heavy-heavy trucks and transit buses. Provisions for in-use audits to ensure compliance with the useful-life requirements, and possible penalties and/or recall if the requirements are found not to be met, are also included in the regulations.

The EPA-defined "useful life" for medium-heavy and heavy-heavy duty engines is reasonably representative of the mileage to the first overhaul. There is presently no effective regulation of heavy-duty engine emissions after overhaul. Since all of the critical emissions-related components on a heavy-duty engine are rebuilt or replaced during overhaul, this is a serious omission. Engine rebuilding practices that may affect emissions have been investigated by another ARB contractor (Sierra Research, 1987).

3.0 IDENTIFICATION OF EMISSIONS-RELATED DEFECTS

The first task addressed in this study was to compile a list of the types of wear, malmaintenance, and/or tampering with emission controls that are likely to be common in heavy-duty diesel engines, and which are likely to result in significant excess emissions. This was also one of the most critical tasks, since this list played a major role in guiding the subsequent investigation. The resulting list of significant emissions-related defects for heavy-duty diesel engines is shown in Table 3-1.

In developing the list in Table 3-1, we relied heavily on previous work (Weaver, 1984a; Weaver et alia, 1984) by project staff in the area of diesel emissions control, and on the professional expertise of Messrs. Macie LaMotte and Doug Decker--diesel mechanics at the Colorado Department of Health who collaborated with Radian on this project. These sources were supplemented by reference to the technical literature (including manufacturer comments on the recent EPA heavy-duty emissions standards), and discussions with the manufacturers themselves and with a selection of experienced diesel mechanics and fleet maintenance managers.

The emissions-related defects listed in Table 3-1 are divided into groups according to the engine system or process involved in the problem. The defects in each group are discussed separately below.

Effects of Injection Timing Changes

Changes in the timing of the fuel-injection process relative to the engine's rotation can significantly affect emissions, especially in direct-injection (DI) engines. For best power and fuel economy, the beginning of fuel injection is usually timed to occur about 15 to 20 degrees before the piston reaches its highest point (top-dead-center or TDC). This allows the fuel time to ignite, and results in most of the fuel being burned near TDC,

TABLE 3-1. COMMON TYPES OF EMISSIONS-RELATED DEFECTS IN HEAVY-DUTY DIESEL TRUCKS

Defect	Likely Cause
Injection Timing Changes	
Timing Retarded	Wear/Malmaintenance
Timing Advanced	Tampering/Malmaintenance
Fuel Injection Problems	
Minor Injector Problem	Wear
Moderate Injector Problem	Wear
Severe Injector Problem	Wear/Bad Fuel
Fuel Air Ratio Problems	
Puff Limiter Misset	Tampering/Malmaintenance
Puff Limiter Disabled	Tampering
Maximum Fuel Too High	Tampering
Clogged Air Filter	Malmaintenance
Turbocharger Worn	Wear
Turbocharger Wrong Type	Tampering
Intercooler Clogged	Malmaintenance
Other Air-Supply Problems	Malmaintenance
Other Engine Problems	
Improper Rebuilding	Tampering/Malmaintenance
Excessive Oil Consumption	Wear
Engine Mechanical Failure	Malmaintenance
Future Technologies	
Electronic Controls Failed	Malmaintenance
Electronic Controls Tampered	Tampering
Catalytic Converter Removed	Tampering
Trap Bypassed	Tampering
Trap Failed/Removed	Tampering
EGR System Disabled	Tampering

where the temperature and pressure are highest. This provides the maximum amount of expansion work, but the high temperature and pressure result in high NO_x emissions.

"Retarding" the injection timing (moving it closer to TDC) results in more fuel burning after the start of the expansion stroke, where pressures and temperatures are lower. This reduces NO_x emissions, at the cost of an increase in HC (especially at light loads), particulate matter, and fuel consumption. Severely retarded injection timing also impairs engine power, cold-starting, and drivability. To comply with California's stringent NO_x standards for heavy-duty engines, California-model diesel engines typically have significantly retarded injection timing compared to the equivalent engine built to Federal standards. These engines tend to have less power and consume 5-10 percent more fuel than Federal engines. They also tend to have higher particulate emissions, and may be smokier and inferior in acceleration capabilities.

The mechanical factors affecting injection timing are different for each type of fuel injection system. For pump-line-nozzle systems, any rotation of the pump with respect to its driveshaft will affect the injection timing. Proper angular positioning of the pump when it is installed or re-installed is critical, since even a few degrees of rotation can significantly affect emissions. Many pump-line-nozzle systems incorporate an injection timing advance mechanism, which shifts the phase angle between the pump and its driveshaft as a function of speed and/or load. These systems can malfunction, and they may be attractive targets for tampering.

In DDA mechanical unit injector systems, injection timing is set by adjusting the clearance between the injector and the rocker arm. This dimension must be checked and reset periodically, due to wear in the injector linkages. DDA provides different clearance gages (resulting in different injection timing) for Federal and California-model engines. Some mechanics experienced with DDA engines indicated that it is not uncommon to reset clearances on California engines using the Federal gage.

For Cummins unit injector systems, injection timing is determined by shims in the cam follower box, and is also affected by wear in the injector drive linkage. Excessive wear not only retards the injection timing, but also prevents the injector plunger from seating fully. This prevents a sharp cutoff of fuel flow at the end of injection, and can markedly increase HC and PM emissions.

Recent Cummins California-model engines incorporate either a mechanical or hydraulic timing control mechanism. This mechanism shifts the cam followers back and forth to advance the injection timing at light loads. By tampering with the system, however, it can be made to remain in the advanced position. Some mechanics familiar with the Cummins system have indicated that tampering with these systems is common.

Injection timing may be retarded from the manufacturer's specification as a result of improper maintenance or adjustment (for instance, improper mounting of the pump, or mis-setting injector clearances on unit-injector systems), or as a result of wear in the Cummins and DDA systems. Timing advanced from the manufacturer's specification may also be due to improper maintenance, or it may result from deliberate tampering. Tampering with injection timing is probably most prevalent on California engines, since advancing the timing on these engines is popularly believed to improve performance and fuel economy. Advancing the timing on Federal engines offers little advantage. With either California or Federal engines, advancing the injection timing increases peak cylinder pressures, and can result in engine damage. Despite this, at least two Federal engines in the recent EPA/EMA in-use study (EMA, 1985) had their timing significantly advanced.

Advanced timing due to maintenance errors is also possible. This type of error is much less likely to be detected and corrected than a corresponding error in the other direction. Excessively retarded timing impairs performance and increases smoke, and is likely to provoke a driver complaint. A moderate advance in injection timing on the other hand, will either have little obvious effect (in Federal engines) or will make the engine seem to run better (in California models), and is not likely to provoke a complaint in either case.

Effects of Fuel Injection Problems

In direct-injection (DI) engines, the rate and effectiveness of mixing between the fuel and the air are determined in large part by the fuel injection system. The performance and emissions of DI engines are thus extremely sensitive to the condition and proper operation of this system. Indirect-injection (IDI) engines are less sensitive to injection characteristics, since mixing in these engines is controlled largely by the air in the prechamber. Sufficiently serious injector problems can dramatically affect emissions even in IDI engines, however.

Fuel injectors may deteriorate as a result of wear, or as a result of hard coky deposits forming on the injector tip. Worn injectors may leak fuel into the combustion chamber, or may allow "secondary injections" during the expansion stroke. They may also suffer from low injection pressure and/or a degraded spray pattern, both of which tend to reduce the effectiveness of mixing. Deposit formation can plug the injector orifices and/or degrade the spray pattern. All of these problems tend to increase smoke and HC emissions, and to degrade power and fuel economy. Depending on the type of problem and its severity, a decrease in NO_x emissions may also occur.

Injector problems vary in severity along a continuum from minor to catastrophic. For analytical purposes, we have divided this range into three levels: minor, moderate, and severe. Minor injector problems are likely to go unrepaired until the next routine maintenance interval. They include minor wear and leakage of the injectors, or slight deposit formation and plugging.

These are not sufficient to impair engine operation noticeably, but can still have a measurable effect on emissions.

Moderate injector problems include moderate wear, moderate fouling and plugging by deposits, and so forth. These problems are severe enough to produce a noticeable (but still small) degradation in performance and fuel economy, as well as a marked increase in smoke. Fleet operations and most independent line-haul operators would normally repair or replace these injectors at the first convenient opportunity. Where maintenance is less scrupulous (e.g., in many small fleets, short-haul, and agricultural operations) this level of problem might not be addressed for some time.

Severe injector problems are the result of seriously worn, badly fouled, badly leaking, or mechanically damaged injectors. These might result from using contaminated fuel, from mechanical failure of the injection system, or a serious mechanical maladjustment. These problems would result in significant impairment of engine performance and fuel economy, and--if allowed to continue--could adversely affect engine life as well. Trucks with this level of problem tend to smoke badly, even in steady-state, road-load operation, and can easily be picked out on the road. Problems of this magnitude should cause all but the most marginal operators to pull the truck out of service immediately for repairs. A significant number of trucks with this level of smoke were observed in our visual smoke survey, however.

Effects of Air-Fuel Ratio

The ratio of air to fuel in the cylinder has a major effect on smoke and particulate emissions, and a lesser effect on NO_x. At high air-fuel ratios, very little soot is emitted in a properly functioning engine. As the air-fuel ratio decreases, soot emissions increase. This increase is not linear, however. Up to a point (known as the smoke limit) smoke density and particulate emissions increase only slowly with decreasing air-fuel ratio;

beyond this point, they rise very rapidly with any further decrease. This typically occurs at an air-fuel ratio of about 21.

The maximum power obtainable from a naturally-aspirated (non-turbocharged) engine is normally smoke-limited--that is, the amount of fuel that can be burned per stroke is limited by the amount of air the cylinder can hold. In turbocharged engines, on the other hand, increasing the amount of fuel injected increases the energy in the exhaust gases, so that the turbocharger spins faster and pumps more air into the engine. Air-fuel ratio is usually not the power-limiting factor in turbocharged engines. Instead, maximum power is limited by the mechanical strength of the engine, or by the speed capabilities of the turbocharger. For this reason, turbocharged engines usually emit less smoke at full power than naturally-aspirated engines.

It takes a finite amount of time for a diesel engine turbocharger to respond to an increase in fuel input by spinning faster and pumping in more air. In a full-power acceleration from idle, airflow can take as long as a second or two to stabilize at the full-power level. If the engine were permitted to pump in the normal full-power fuel quantity in the meantime, very high smoke and particulate emissions would result. For this reason, turbocharged engines on highway vehicles make use of transient smoke limiting devices or "puff limiters" to reduce the permitted maximum fuel rate until the turbocharger comes up to speed. Most heavy-duty engine manufacturers use some sort of air-pressure measuring device, such as an anaeroid bellows, to control the maximum fuel rate as a function of inlet manifold pressure. Some Detroit Diesel Allison engines still use a throttle delay device, which gives less precise control.

In limiting the maximum fuel to reduce smoke and particulate emissions, the puff limiter also reduces the maximum engine power during the first second or two of acceleration. This impairs the engine's responsiveness and affects the driver's perception of truck performance. This creates a significant incentive to tamper with the device. The results of the engine rebuilders and mechanics survey and our visual smoke survey indicate that such tampering is rampant. Many puff limiters have an adjusting screw or other setting to permit the maximum fueling rate to be set to manufacturer's specifications for the particular engine. These settings are commonly re-adjusted by drivers and mechanics to increase the maximum fuel rate, thus increasing transient smoke emissions. The puff limiter may also be defeated or removed entirely. This can result in thick clouds of black smoke upon acceleration.

Another common form of tampering which affects emissions concerns the setting of the maximum steady-state fuel level. The maximum amount of fuel allowed to be injected per stroke directly determines the maximum power output from the engine. In Detroit Diesel unit-injector engines this limit is a built-in function of the injectors, while in the Cummins unit-injector system it is determined by a replaceable component (the "button"). In most other types of fuel injection systems this level is determined by an adjusting screw. These screws are normally tamper-sealed; breaking the seal voids the engine warranty. Despite this, increasing the engine power level by "turning up" the fueling rate is an extremely common practice among independent owner-operators and some fleet drivers. (See, for instance, American Trucker magazine, November, 1985).

In naturally-aspirated engines, increasing the maximum fuel rate can dramatically increase smoke density and particulate emissions at full load. Turbocharged engines are less sensitive to this setting, since increasing the fuel flow into the engine simply causes the turbocharger to turn faster and pump in more air. Thus, the effect of increasing the maximum fuel setting is mostly to increase the mechanical stress on the engine--the emissions effects (on a grams/BHP-hr basis) are considered to be relatively minor, at least for moderate increases. Large increases are likely to damage the engine, possibly resulting in a large (but temporary) increase in emission rates.

In addition to tampering, any of a number of maintenance-related problems can impair the air supply to the engine, thus increasing smoke and particulates. By far the most common such problem is a clogged air cleaner. resulting in an excessive pressure drop and reduced airflow into the engine. Air cleaners are a regular maintenance item in manufacturer's checklists, and most manufacturers now equip their engines with an inlet pressure gage, a "flip-out" indicator of excessive pressure drop, or both. Despite these preventive measures, moderately-to-badly clogged air cleaners are common, especially in applications such as short-haul trucking, small fleets, and agricultural hauling, where regular preventive maintenance is less common than in long-haul service.

A number of other problems can impair the air supply and increase emissions from turbocharged engines. These include deterioration of the turbocharger itself, air or exhaust leaks, fouling or deterioration of the intercooler, and excessive exhaust backpressure. All of these problems result in reduced turbocharger boost, and thus less air to the engine. The reduced air-fuel ratio increases particulate emissions and fuel consumption, but may reduce NO_x slightly. Intercooler deterioration results in hotter intake air, however, which increases NO_x.

Air supply problems can noticeably reduce power output and performance as well as fuel economy, so one would expect them to be repaired fairly quickly if they become too severe. Our survey of engine rebuilders and mechanics indicates that these problems are fairly common, however. One reason for this may be their cost--replacing a turbocharger or an intercooler is a fairly expensive operation.

Another air supply-related problem which could affect emissions is the use of a non-standard turbocharger. Some replacement turbochargers may be functionally equivalent to the original, but some probably are not. A turbocharger with inadequate pressure boost or transient response could increase particulate emissions, while one with excessive boost could increase NO_x (as well as possibly damaging the engine). High-boost turbochargers tend to have poorer transient and low-speed performance, so they may increase PM emissions in these modes.

Improper Rebuilding

Heavy-duty engines are normally rebuilt at least once, and often two or three times during their operating lifetimes. During rebuild, key emissions-related components and systems such as the fuel injection system, turbocharger, valve gear, pistons, etc. are removed and refurbished or replaced. If this is done using the original manufacturer's parts (or equivalents), and following the manufacturer's specifications, this should result in emission levels very close to the new-engine values. On the other hand, sloppy rebuilding, use of non-standard parts, or failure to follow manufacturer's specifications is likely to result in increased emissions. Of particular concern in California is the prospect of California-model engines being rebuilt using the parts and specifications for the equivalent Federal engine. This would result in a substantial increase in NOx emissions, but a decrease in smoke, particulates, and fuel consumption.

Engine rebuilding practices in California were investigated by another ARB contractor (Sierra Research, 1987). This study concluded that improper rebuilding was not a major factor in increasing emissions. To the extent that improper rebuilding occurs, it would mostly show up as advanced injection timing, increased maximum fuel rate, or a non-standard turbocharger --all of which are accounted for separately. Therefore, no separate consideration of improper rebuilding is necessary.

Other Engine Problems

Major mechanical problems such as turbocharger failure, collapsed piston rings, or excessive oil consumption can all result in very large increases in particulate and HC emissions. Common causes of high oil consumption are mechanical wear of piston rings and cylinder liners, stuck piston rings, carbon deposits in the top land of the piston, or a bad turbocharger oil seal. Except for the turbocharger oil seal, correcting these problems requires overhauling the engine, at a cost of $3,000 to $8,000.

Engines with major mechanical problems tend to be pulled out of service fairly quickly, to keep from damaging the engine. An engine with high oil consumption may continue to be used for some time before being rebuilt, however. Although the fraction of trucks with major mechanical or oil consumption problems is small, they tend to be gross emitters, with particulate and HC emissions four to ten times the levels of properly-functioning engines. Thus, their contribution to total excess emissions is not insignificant.

Future Technologies

Future Federal and California emissions standards for heavy-duty diesel engines will require the use of advanced emission control techniques, some of which may significantly affect the cost, fuel economy, and performance of the vehicle. Emission control malfunctions and/or deliberate tampering are expected to result in significant excess emissions from emission-controlled heavy-duty vehicles, as they do for emission controlled light-duty vehicles today. Due to the economic incentives involved, and the greater mechanical sophistication of truck owners and operators, we expect tampering to be much more common on heavy-duty trucks than on current light-duty vehicles.

To meet future NO_x and particulate standards, many engine manufacturers are introducing advanced engine control systems. These systems include microprocessor control of the engine governor and fueling rate, and usually control injection timing as well. These sophisticated control systems will eliminate or greatly reduce both the opportunities and the incentives to tamper with existing mechanical emissions controls, such as the injection timing, puff limiter, and maximum fuel rate. At the same time, however, they will introduce a range of new potential problems such as sensor malfunctions, electronic failures, etc. These systems include a "limp-home" capability, so that most electronic or sensor failures will not completely incapacitate the engine. However, emissions from an engine in "limp-home" mode would probably be increased significantly.

Most of the electronic control systems being developed make use of a standard "generic" fuel injection and control system which is customized to the needs of a particular engine model and application by adding a programmable read-only memory (PROM) chip containing the "map" of proper engine settings as functions of load, speed, and other variables. Based on current experience with electronic controls in light-duty vehicles, it seems inevitable that alternative PROMs, containing engine maps optimized for power, performance, and fuel economy rather than low emissions, will rapidly appear on the market. These PROMs will probably be identified as intended for "racing" use only (heavy-duty diesel truck racing is a rapidly growing sport), but will inevitably find their way into on-highway vehicles as well. So far, only one engine manufacturer appears to have given serious thought to ways to prevent this. Depending on the system design, other forms of tampering with the control system (e.g., by disabling sensors or substituting a false signal) may also be feasible.

Most heavy-duty diesel manufacturers now expect to be able to meet the 1991 truck emissions standards without a trap-oxidizer, at least in heavy-heavy and some medium-heavy engines (Weaver and Klausmeier, 1987). Some, especially in the medium-heavy class, may still require a catalytic converter to meet the standards, however. For light-heavy engines, Radian projects that either a trap or a catalytic converter will be required in nearly all cases. The 1991 bus standard and 1994 truck standards will require trap-oxidizers on all new heavy-duty vehicles.

Catalytic converters on heavy-duty trucks will require use of low-sulfur fuel, much as those on light-duty gasoline vehicles require unleaded. Aside from this requirement, catalytic converters on light-duty vehicles impose no significant disadvantages except for initial cost. Despite this, the tampering and removal rate for catalytic converters in light-duty trucks was nearly 20 percent in the most recent EPA tampering survey (EPA, 1984), while for older trucks the tampering rate exceeded 50 percent. It appears likely, therefore, that tampering with catalytic converters on heavy-duty diesel trucks may also be fairly common. The most common form of tampering would be to remove the converter, replacing it either with a straight pipe or with an empty catalyst housing.

Trap-oxidizers can dramatically reduce particulate and smoke emissions, but they also reduce power, performance, and fuel economy somewhat, may require expensive maintenance and/or periodic replacement, and are likely to be perceived as a safety hazard by owners and drivers. These disadvantages (from the operators viewpoint) can be eliminated by bypassing or removing the trap. Nearly all of the trap-oxidizer systems now under development include a provision for bypassing the trap during regeneration (Weaver and Klausmeier, 1987). These systems can easily be disabled by locking the bypass valves. Traps will also be fairly easy to remove outright. Under these circumstances, and in the absence of any strong incentive to the contrary, it would be very surprising if a large fraction of trap-oxidizers were not bypassed, removed, or otherwise tampered with. Failure to maintain or replace the trap-oxidizer system when necessary is also expected to be common. This will ultimately result in its failure, with a consequent increase in particulate emissions to uncontrolled levels.

Exhaust gas recirculation (EGR) is a powerful NO_x control technique for diesels, but it requires increased oil change frequency and adversely effects engine durability. Because of this, EGR has been used on only a few California-model heavy-duty engines to date, although it is commonly used in light-duty engines. We project that some light-heavy and medium-heavy engines will use EGR to comply with the 1991 NO_x standards. Tampering with EGR systems is fairly common even on light-duty vehicles. For heavy-duty engines, the adverse effects of EGR on maintenance cost and engine life would provide a much greater motive for tampering, and we anticipate that this will be common.

4.0 MODELING EXCESS EMISSIONS FROM HEAVY-DUTY DIESEL VEHICLES

The preceding section presented a qualitative discussion of the reasons for excess emissions from heavy-duty diesel vehicles. In order to evaluate the cost-effectiveness of an I/M program, however, it is essential to have quantitative estimates of the overall increase in emissions of each pollutant from the total heavy-duty diesel fleet as a result of tampering and malmaintenance, with and without an I/M program in place. To estimate these quantities, Radian constructed an elaborate computer model using the Lotus® spreadsheet program. This section discusses the model structure and the supplementary data (such as baseline emissions and vehicle-miles travelled) which enter into it. Key input data to this model are the estimated frequency of occurrence of specific emissions defects, and the estimated impact of each type of defect on emissions. These estimates are presented in Sections 5.0 and 6.0, respectively.

Figure 4-1 diagrams the structure of the model developed for this project. Like most vehicle emissions models, it defines a number of vehicle classes, then combines two disparate types of data for each class. The vehicle classification used in the model includes finer subdivisions and much more detail than that used in developing ARB's present emissions inventory. This classification is discussed in Section 4.1.

The first type of data developed in the model is a set of "emission factors" describing the average pollutant emissions per unit of distance travelled by vehicles of different classes, expressed in grams of pollutant per mile (g/mi). The emission factors for each class of vehicles are uniquely determined by the technical characteristics of the vehicles in use in that class. The structure of the submodel which estimates these emission factors is described in Section 4.2. The resulting emission factors (for the baseline case, assuming no I/M program is in effect) are presented in Section 7.0.

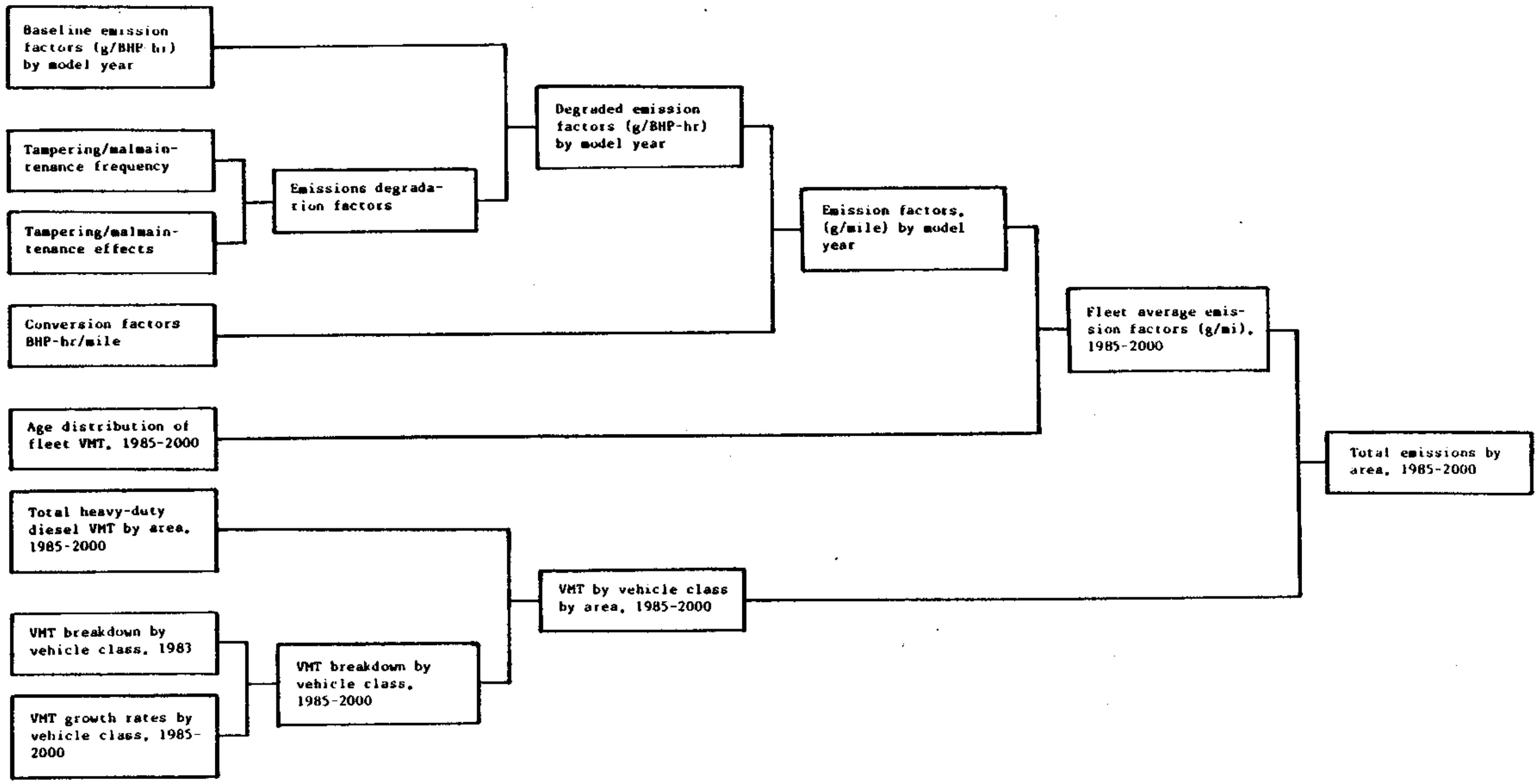


Figure 4-1. Structure of the Diesel Engine Emissions Model

The second type of data used in the model consists of estimates of the number of daily vehicle-miles travelled (VMT) by vehicles in each class, both statewide and in various geographic areas. These are determined by statewide and regional traffic data. Radian's estimates of regional and statewide VMT followed an approach very similar to that used in developing ARB's existing emissions inventory. This approach is described in Section 4.3.

Multiplying the estimated VMT for each class and year by the emission factor for that class and summing gives the estimated total emissions statewide and in each geographic area. The results of these calculations for the baseline case are presented in Section 8.0.

4.1 Heavy-Duty Vehicle Classes Used in the Model

For modeling purposes, all heavy-duty diesel vehicles were placed in one of eleven classes. The four-way classification of heavy-duty vehicles into light-heavy, medium-heavy, heavy-heavy, and transit bus was described in Section 2.1. Each of these classes can be further subdivided into vehicles registered in California, and those with out-of-state registrations. This subdivision is important, since most types of I/M programs would apply only to vehicles registered in California.

For emissions purposes, it is also important to distinguish between California-registered vehicles equipped with California engines and those with engines certified to the Federal emissions standards. New heavy-duty vehicles purchased in California are required to use engines certified to California's stricter NO_x standards. Vehicles with Federal engines may be imported and registered under either of two legal provisions, however. One provision applies to used vehicles, which may be imported as long as their odometers show at least 7,500 miles of use. Since this is only about one month's mileage for a typical line-haul truck, it is likely that many such vehicles are brought in.

The other exception applies to vehicles used in interstate commerce. These vehicles may register under one of two interstate agreements which provide for pro-rata sharing of registration fees with other states. The Department of Motor Vehicles has interpreted the law as permitting vehicles registered under these pro-rata agreements to use Federal engines, and it is likely that nearly all of them do. Nearly all of these vehicles are heavy-heavy trucks used in line-haul freight service.

Table 4-1 lists the eleven categories of vehicles defined by this three-way classification system (out-of-state transit buses, which would have been a twelfth category, have been omitted for obvious reasons). Although all of these classes are considered in the model, not all are equally important. As will be brought out in Section 8.0, most heavy-duty diesel emissions are due to the three classes of heavy-heavy duty trucks, and most of the remainder are due to California-model medium-heavy. The other classes listed are fairly minor contributors to the overall emissions picture, accounting for less than 20 percent of the total altogether.

4.2 Description of the Emission Factor Submodel

For emission inventory use, vehicle emission factors are conventionally expressed in terms of grams of pollutant emitted per vehicle-mile travelled in a given year. In the case of heavy-duty vehicles, this introduces two complications. Due to the wide variation in vehicle size and weight, emissions standards are applied to heavy-duty engines, not vehicles, and are expressed in terms of emissions per unit of work produced (i.e., grams per brake horsepower-hour or g/BHP-hr). To convert these data to g/mi requires an extra step, involving an estimate of the average engine work requirement per mile travelled for each type of vehicle. In addition, emissions standards apply to vehicles manufactured in a given model year, while the vehicles actually on the road were manufactured at many different times. It is necessary, therefore, to aggregate the emission factors from different model years

TABLE 4-1. HEAVY-DUTY VEHICLE CLASSIFICATIONS USED IN THE MODEL

Classification	Percent of Total VMT 1987	2000
Heavy-Heavy Duty		
California Registered/California Engine	20.6	20.0
California Registered/Federal Engine	20.6	20.0
Out-of-State Registered	13.9	12.7
Medium-Heavy Duty		
California Registered/California Engine	22.1	22.4
California Registered/Federal engine	5.9	5.9
Out-of-State Registered	7.8	7.5
Light-Heavy Duty		
California Registered/California Engine	4.8	7.8
California Registered/Federal Engine	0.6	1.0
Out-of-State Registered	0.2	0.3
Transit Bus		
California Registered/California Engine	2.3	1.8
California Registered/Federal Engine	1.1	0.8

according to their contribution to the total VMT travelled in a given calendar year.

Section 4.2.1 below presents our estimates of baseline emission factors for well-maintained engines in terms of g/BHP-hr. Section 4.2.2 then describes how the model calculates the changes in emission factors as a result of tampering and malmaintenance. Section 4.2.3 describes the calculation of emission factors in g/mile from the g/BHP-hr data. Section 4.2.4 describes the aggregation of model year data to produce emission factors by calendar year.

4.2.1 Baseline Emission Factors: Grams Per Horsepower-Hour

The starting point for the emission factor model is a set of baseline emissions factors. These factors define the NO_x, HC, and PM emissions (in g/BHP-hr) that would be expected from an engine in proper working condition. These factors were estimated separately for engines in each class of vehicles (light-heavy, medium-heavy, heavy-heavy, and transit buses), and for each model year. For the 1977-1989 period, when California emissions standards differ significantly from Federal standards, they were estimated separately for Federal and California-model engines as well. These estimates are summarized in Table 4-2.

The values in Table 4-2 are based on the Federal Heavy-Duty Transient Cycle emissions test. This test was selected for two reasons: representativeness and data availability. Unlike the older 13-mode (steady-state) test procedure, the Federal Transient procedure is intended to simulate urban operation, including transient effects. Much rural highway driving more closely resembles steady-state operation. The differences between NO_x emissions in the transient and steady-state tests are small, so the NO_x emission factors shown in Table 4-2 can be considered representative of both rural and

TABLE 4-2. BASELINE EMISSION FACTORS USED IN THE MODEL (g/BHP-hr)

	Oxides of Nitrogen	Unburned Hydrocarbons	Particulate Matter
Light-Heavy Duty			
1960 - 1976	9.0	1.10	0.80
1977 - 1979	4.0	0.80	0.80
1980 - 1987	4.5	0.80	0.60
1988 - 1990	5.5	0.70	0.55
1991 - 1993	4.8	0.40	0.22
1994 - 1995	4.8	0.30	0.08
Medium-Heavy Duty			
1960 - 1976	9.0	1.10	0.70
1977 - 1979	6.0[a]/7.6[b]	1.10	0.90[a]/0.70[b]
1980 - 1987	5.0[a]/7.5[b]	0.90	0.80[a]/0.70[b]
1988 - 1990	5.5[a]/7.0[b]	0.70	0.55[a]/0.45[b]
1991 - 1993	4.8	0.40	0.22
1994 - 1995	4.8	0.30	0.08
Heavy-Heavy Duty			
1960 - 1976	9.0	0.80	0.70
1977 - 1979	6.0[a]/7.5[b]	0.80	0.90[a]/0.70[b]
1980 - 1987	5.0[a]/7.0[b]	0.80	0.80[a]/0.70[b]
1988 - 1990	5.5[a]/7.0[b]	0.60	0.55[a]/0.45[b]
1991 - 1993	4.8	0.30	0.22
1994 - 1995	4.8	0.20	0.08
Transit Bus			
1960 - 1976	9.0	1.10	0.60
1977 - 1979	6.0[a]/9.0[b]	1.10	0.75[a]/0.60[b]
1980 - 1987	5.0[a]/9.0[b]	1.10	0.65[a]/0.60[b]
1988 - 1990	5.5[a]/7.5[b]	0.80	0.45[a]/0.35[b]
1991 - 1993	4.8	0.40	0.08
1994 - 1995	4.8	0.40	0.08

[a] California-Model Engines and Federal 1990 models
[b] Federal-Model Engines (except 1990)

urban operation. The transient cycle normally shows greater HC and PM emissions than the steady-state test, however. Thus, the HC and PM emission factors shown in the table may be somewhat overstated for rural driving.

The values shown in Table 4-2 are Radian estimates, based on a variety of sources. Ideally, these values should be based on a sales-weighted average of Federal certification test data for each engine class. Unfortunately, the data required to support this calculation are unavailable. The Federal transient test has only been used for emissions certification in the last few years, so transient-test data for earlier years are unavailable. In addition, particulate emissions data are not reported in the Federal certification listings, as diesel particulate matter will not become a regulated pollutant until model year 1988.

As a result, the baseline emission factors used were based on numerous incomplete sources, including Federal certification test data for the last few years, transient-test data reported in manufacturer's submissions to EPA, the EPA/EMA in-use emissions study (EMA, 1985), and a summary of then-available transient test data included in (Weaver et al., 1984), and reproduced in this report as Figure 6-1. These were combined with a certain amount of engineering judgment. Emissions from older engines were were estimated from the available (steady-state) data, confidential data provided by engine manufacturers (where available), general trends in engine design and emissions, and other considerations such as the effects of California's low NO_x standards. Estimates of future emissions values were based on another recent Radian study (Weaver and Klausmeier, 1987), which relied heavily on confidential data from manufacturers.

4.2.2 Tampering And Malmaintenance Effects On Emission Factors

In order to calculate the effects of tampering and malmaintenance on emissions, Radian estimated the frequency of occurrence of each of the types of emissions defects identified in Section 3.0 in each class of heavy-duty diesel vehicles, as well as the effects of each type of emissions defect on HC, NO_x, and PM emissions, and fuel economy. These estimates are presented in

Sections 5.0 and 6.0, respectively. In order to calculate the effects of these defects on the overall emission factors, however, several more steps are necessary. The first step is to multiply the fractional change in emissions (EF) due to each defect by the estimated frequency of occurrence (F) of that defect in vehicles of each class. The result of this calculation is the effect that that defect has on the average emission factor for all vehicles of the given class.

$$\Delta EF_{(ind.\ veh.)} * F = \Delta EF_{(class)} \qquad (4\text{-}1)$$

For instance, if a particular defect were found in 10 percent of the vehicles of a given class, and resulted in a 50 percent increase in emissions, then the increase in the overall emission factor for that class due to that defect would be 0.50 x 0.10 = 0.05 or 5 percent.

The next step is to combine the effects of each type of defect to estimate the total effects of tampering and malmaintenance on emissions. These effects are not strictly additive, since more than one type of defect may be found in any individual vehicle. Defects of different types typically have a multiplicative effect--for instance, removing a trap-oxidizer might increase particulate emissions by 400 percent (5 times), while a moderate injector problem would increase them by 100 percent (double). The combination of the two, however, increases emissions by 900 percent (10 times), not 500 percent. The interaction between other types of defects such as injection timing and air-system problems is less well-defined, but the multiplicative model is considered to give a reasonably good approximation in these cases as well.

Certain groups of defects, however, are mutually incompatible, or represent varying severity levels of the same problem. Examples of the former include injection timing retardation and injection timing advance, which clearly cannot occur simultaneously in the same vehicle. Within these groups, the effects of multiple defects are additive, not multiplicative. In addition, the "gross emitter" categories (severe injection problems, excessive oil consumption, and engine mechanical defects) include engines typically having multiple defects, and it would be inaccurate to multiply these effects by those of the other problems considered.

Thus, to calculate the total effects of tampering and malmaintenance on emissions, it is necessary to sum the effects of the individual defects within each group, and then to multiply the effects of the different groups together, with a separate accounting for the "gross emitter" categories. This calculation is diagrammed in Figure 4-2.

4.2.3 Conversion Factors: Grams Per Horsepower-Hour To Grams Per Mile

To convert emission factors specified in terms of emissions per unit of work output to factors combinable with the available data on vehicle-miles travelled, it was necessary to estimate the amount of engine work required to propel a vehicle a given distance. This quantity is obviously very dependent on the size, aerodynamic characteristics, and driving patterns of the vehicle involved. For our purpose, separate conversion factors (expressed in units of BHP-hr per mile) were needed for each vehicle class.

This conversion factor can readily be calculated for any individual vehicle by comparing engine dynamometer data on fuel-consumption per BHP-hr with vehicle operation data on fuel consumption per mile. Energy and Environmental Analysis (1984) performed these calculations for light-heavy, medium-heavy, and heavy-heavy duty trucks, using both past and projected future data. EPA (Smith, 1985) subsequently modified these calculations slightly, and developed a similar set of conversion factors for transit buses. The conversion factors used in the Radian model are based on the EPA conversion factors, which are also used in EPA's MOBILE3 model.

The EPA conversion factors in Smith (1985) are calculated separately for a number of different MVMA truck weight classes, and then aggregated according to each class' contribution to total diesel VMT. To complicate matters further, the weight class breakdown used for past years (through 1979

Groups	Calculations
1. Injection timing advanced 2. Injection timing retarded 15. Electronics failed 16. Electronics tampered 19. EGR Disabled	$\left[(1.0 + \Delta EF_1 + \Delta EF_2 + \Delta EF_{15} + \Delta EF_{16} + \Delta EF_{19})\right.$
	x
3. Minor injection problems 4. Moderate injection problems	$(1.0 + \Delta EF_3 + \Delta EF_4)$
	x
6. Puff limiter mis-set 7. Puff limiter disabled	$(1.0 + \Delta EF_6 + \Delta EF_7)$
	x
8. Maximum fuel high	$(1.0 + \Delta EF_8)$
	x
9. Clogged air filter	$(1.0 + \Delta EF_9)$
	x
10. Wrong/Worn Turbo	$(1.0 + \Delta EF_{10})$
	x
11. Intercooler clogged	$(1.0 + \Delta EF_{11})$
	x
12. Other air problems	$(1.0 + \Delta EF_{12})$
	x
17. Catalytic converter removed 18. Trap removed/disabled	$\left.(1.0 + \Delta EF_{17} + \Delta EF_{18})\right] - 1.0$
5. Severe injection problems	$+ \Delta EF_5$
13. Mechanical failure	$+ \Delta EF_{13}$
14. Excess oil consumption	$+ \Delta EF_{14}$
	ΔEF_{total}

Figure 4-2. Calculating Combined Effects of Tampering/Malmaintenance-Related Defects on Emissions

was different from that used for 1982 and later. The class-specific conversion factors and weighting factors developed by EPA are shown in Table 4-3, along with the class-specific conversion factors used in this study.

For years through 1979, Radian used the EPA factors for Class IIb for our light-heavy duty vehicle class. Conversion factors for the medium-heavy duty class were taken as the weighted average of those for classes III-V, VI, VII, and VIII. The weights used in the averaging for classes III-V, VI, and VII were the EPA weights shown in the table. For Class VIII, only 30 percent of the EPA weighting was used in the medium-heavy duty calculation. The other 70 percent of Class VIII vehicles were assumed to be in our heavy-heavy duty class.

For years after 1979, Radian used the EPA factors for MVMA classes II(b) through IV to represent our light-heavy class. The conversion factor for our medium-heavy class was calculated as the weighted average of the EPA factors for classes V, VI, VII, and VIII(a), using the EPA weightings. EPA class VIII(b) was taken as identical to our heavy-heavy weight class. Conversion factors for transit buses in all years were taken directly from the EPA values.

As shown in Table 4-3, EPA developed conversion factor estimates for only a limited number of years, ranging from 1962 to 1997. Conversion factors for years not shown in the table were obtained by linear interpolation (for years before 1997), and by carrying forward the 1997 values for years 1998-2000.

4.2.4 Calculating Fleet-Average Emission Factors

Up to this point, the emission factor estimates developed applied to vehicles of a given vehicle class and model year. However, the available VMT data are expressed in terms of total vehicle miles traveled in a given calendar year. In order to combine the two sets of data, it was necessary to calculate the fleet-average emissions factor for the vehicles of a given class

TABLE 4-3. CALCULATION OF EMISSIONS CONVERSION FACTORS USED IN THE MODEL

EPA Conversion and VMT Weighting Factors Used in the Calculation[1]

Model Year	Class IIb C.F.	Class IIb Weight	Class III-V C.F.	Class III-V Weight	Class VI C.F.	Class VI Weight	Class VII C.F.	Class VII Weight	Class VIII C.F.	Class VIII Weight
1962	0.998	0.000	1.710	0.040	1.714	0.061	2.187	0.246	2.802	0.486
1965	0.998	0.001	1.710	0.042	1.714	0.095	2.187	0.158	2.864	0.592
1967	0.998	0.001	1.710	0.036	1.714	0.093	2.232	0.118	2.970	0.652
1970	0.998	0.000	1.710	0.002	1.749	0.062	2.280	0.068	3.083	0.764
1972	0.998	0.000	1.710	0.002	1.824	0.027	2.280	0.070	3.190	0.817
1975	0.998	0.000	1.710	0.002	1.864	0.044	2.295	0.091	3.260	0.652
1977	0.998	0.001	1.710	0.000	1.871	0.063	2.268	0.091	3.350	0.791
1978	0.998	0.001	1.710	0.000	1.860	0.063	2.198	0.091	3.296	0.791

Model Year	Class II-IV C.F.	Class II-IV Weight	Class VI C.F.	Class VI Weight	Class VII C.F.	Class VII Weight	Class VIIIa C.F.	Class VIIIa Weight	Class VIIIb C.F.	Class VIIIb Weight
1982	0.970	0.126	1.865	0.026	2.260	0.106	3.002	0.244	3.190	0.420
1987	0.964	0.169	1.776	0.043	2.154	0.234	2.863	0.028	3.385	0.421
1992	0.944	0.259	1.765	0.041	2.142	0.209	2.849	0.031	3.106	0.393
1997	0.922	0.247	1.746	0.047	2.115	0.209	2.811	0.034	3.048	0.394

Conversion Factors Used in the Model

Model Year	Light-Heavy[2]	Medium-Heavy[3]	Heavy-Heavy[4]	Transit Bus[1]
1962	0.998	2.272	2.802	4.004
1965	0.998	2.304	2.864	4.004
1967	0.998	2.407	2.970	4.004
1970	0.998	2.673	3.083	4.004
1972	0.998	2.889	3.190	4.004
1975	0.998	2.802	3.260	4.004
1977	0.998	2.860	3.350	4.004
1978	0.998	2.809	3.296	4.004
1982	0.970	2.714	3.190	3.989
1987	0.964	2.166	3.385	3.802
1992	0.944	2.165	3.106	3.782
1997	0.922	2.137	3.048	3.733

[1] Source, Smith, 1984.
[2] EPA Class IIb and Class II-IV data.
[3] Weighted average of EPA Class III-V, VI, VII, and VIII data.
[4] EPA Class VIII and VIIIb data.

in use in a given calendar year. This calculation takes as input the emission factors for each model year and the expected contribution of vehicles of each model year to the total VMT.

For light-heavy, medium-heavy, and heavy-heavy duty trucks, each model year's contribution to the total VMT in each calendar year from 1985 to 2000 was estimated from CALTRANS projections of vehicle registrations by model year for those years (Lynch and Lee, 1986). These were combined with CALTRANS estimates of typical VMT per vehicle as a function of vehicle class and age. Combining these two data sets allowed us to calculate the fraction of the total annual VMT for each class that would be contributed by vehicles of each age group in each calendar year. These data are presented in Tables 4-4 through 4-6.

The Caltrans estimates gave no separate accounting for transit buses. To estimate the VMT mix by model year for buses, Radian relied on a statistical report by the American Public Transit Association (APTA, 1986). This report listed the fraction of all transit buses in use nationwide built in each model year, as of January 1, 1986. This gave a snapshot of fleet com-position in that year. Based on discussions with bus operators, we assumed that relative VMT per vehicle would vary little over the first twelve years of the bus' useful life, and then would decrease by 20 percent for the remainder of its life. This pattern is quite unlike cars and trucks, where VMT per vehicle decline sharply after 5-6 years, but is consistent with the APTA data.

To reflect purchases of new buses for subsequent years, Radian "aged" this distribution by assuming that new buses amounting to 6.6 percent of the fleet would be purchased in each subsequent year, and that buses which had exceeded their 12-year useful lives would be retired to compensate. Since the new buses were assumed to be bought during the year in question, they were assumed to provide only half of the possible VMT in the year of purchase. The

TABLE 4-4. DISTRIBUTION OF VEHICLE-MILES TRAVELLED BY VEHICLE AGE: HEAVY-HEAVY DUTY VEHICLES

Vehicle Age (Years)	Calendar Year 1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
0	0.141	0.127	0.133	0.132	0.130	0.127	0.126	0.124	0.122	0.120	0.119	0.117	0.116	0.115	0.115	0.114
1	0.107	0.181	0.154	0.148	0.145	0.141	0.138	0.136	0.134	0.133	0.133	0.131	0.130	0.130	0.130	0.130
2	0.052	0.096	0.152	0.127	0.123	0.119	0.116	0.114	0.112	0.111	0.112	0.112	0.110	0.110	0.109	0.109
3	0.057	0.043	0.081	0.130	0.111	0.107	0.105	0.102	0.100	0.099	0.099	0.100	0.100	0.094	0.093	0.093
4	0.070	0.047	0.037	0.069	0.114	0.097	0.094	0.092	0.090	0.088	0.089	0.089	0.089	0.087	0.080	0.079
5	0.087	0.057	0.039	0.031	0.060	0.099	0.085	0.082	0.081	0.079	0.079	0.079	0.078	0.080	0.078	0.069
6	0.112	0.071	0.048	0.033	0.027	0.052	0.086	0.074	0.072	0.070	0.070	0.070	0.069	0.070	0.072	0.069
7	0.070	0.091	0.059	0.040	0.029	0.023	0.045	0.074	0.064	0.062	0.069	0.061	0.061	0.061	0.063	0.065
8	0.057	0.056	0.075	0.049	0.034	0.024	0.020	0.038	0.063	0.054	0.054	0.054	0.053	0.053	0.054	0.056
9	0.030	0.045	0.046	0.062	0.041	0.029	0.020	0.017	0.032	0.054	0.047	0.046	0.046	0.046	0.047	0.048
10	0.035	0.024	0.036	0.043	0.051	0.034	0.024	0.017	0.014	0.027	0.045	0.040	0.039	0.037	0.040	0.041
11	0.042	0.027	0.019	0.029	0.030	0.042	0.028	0.019	0.014	0.011	0.023	0.038	0.033	0.033	0.030	0.034
12	0.035	0.032	0.021	0.015	0.023	0.024	0.033	0.022	0.016	0.011	0.009	0.018	0.031	0.027	0.027	0.024
13	0.024	0.026	0.025	0.016	0.012	0.018	0.019	0.026	0.018	0.013	0.009	0.007	0.015	0.025	0.022	0.023
14	0.014	0.018	0.019	0.019	0.012	0.009	0.014	0.015	0.021	0.014	0.010	0.007	0.006	0.012	0.020	0.018
15	0.011	0.010	0.013	0.014	0.014	0.009	0.007	0.011	0.011	0.016	0.011	0.008	0.005	0.005	0.009	0.016
16	0.014	0.008	0.007	0.009	0.010	0.010	0.007	0.005	0.008	0.008	0.012	0.008	0.006	0.004	0.003	0.007
17	0.012	0.009	0.005	0.005	0.007	0.007	0.007	0.005	0.004	0.006	0.006	0.008	0.006	0.004	0.003	0.002
18	0.003	0.008	0.006	0.004	0.003	0.005	0.005	0.005	0.003	0.002	0.004	0.004	0.006	0.004	0.003	0.002
19	0.027	0.024	0.025	0.025	0.023	0.022	0.022	0.022	0.022	0.022	0.002	0.003	0.003	0.004	0.002	0.002
TOTAL	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000

TABLE 4-5. DISTRIBUTION OF VEHICLE-MILES TRAVELLED BY VEHICLE AGE: MEDIUM-HEAVY DUTY VEHICLES

Vehicle Age (Years)	Calendar Year 1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
0	0.128	0.103	0.114	0.121	0.122	0.123	0.122	0.120	0.118	0.116	0.113	0.111	0.109	0.108	0.107	0.107
1	0.123	0.168	0.133	0.138	0.139	0.139	0.139	0.137	0.135	0.134	0.132	0.129	0.128	0.127	0.127	0.127
2	0.099	0.147	0.190	0.149	0.151	0.152	0.152	0.152	0.151	0.150	0.149	0.148	0.146	0.145	0.144	0.143
3	0.086	0.065	0.097	0.128	0.100	0.102	0.103	0.103	0.104	0.103	0.102	0.103	0.102	0.096	0.095	0.095
4	0.104	0.073	0.055	0.084	0.112	0.088	0.089	0.091	0.091	0.092	0.091	0.092	0.092	0.090	0.083	0.082
5	0.099	0.087	0.062	0.048	0.073	0.097	0.076	0.078	0.079	0.080	0.081	0.081	0.081	0.083	0.080	0.071
6	0.106	0.082	0.073	0.053	0.041	0.063	0.083	0.066	0.068	0.069	0.069	0.071	0.071	0.072	0.074	0.071
7	0.075	0.086	0.067	0.061	0.045	0.035	0.053	0.071	0.056	0.058	0.062	0.060	0.061	0.063	0.064	0.067
8	0.045	0.060	0.070	0.056	0.051	0.037	0.029	0.045	0.060	0.047	0.049	0.050	0.051	0.053	0.055	0.057
9	0.024	0.036	0.048	0.057	0.046	0.042	0.030	0.024	0.037	0.049	0.039	0.041	0.042	0.044	0.045	0.048
10	0.028	0.019	0.028	0.041	0.046	0.037	0.034	0.025	0.019	0.030	0.040	0.032	0.033	0.034	0.037	0.039
11	0.027	0.021	0.014	0.022	0.030	0.036	0.029	0.026	0.019	0.015	0.024	0.032	0.026	0.027	0.027	0.030
12	0.021	0.020	0.016	0.011	0.016	0.023	0.027	0.022	0.020	0.015	0.012	0.018	0.025	0.020	0.022	0.021
13	0.015	0.015	0.014	0.011	0.008	0.012	0.017	0.020	0.016	0.015	0.011	0.009	0.014	0.019	0.016	0.017
14	0.008	0.010	0.010	0.010	0.008	0.005	0.008	0.012	0.014	0.011	0.011	0.008	0.006	0.010	0.014	0.011
15	0.005	0.005	0.006	0.007	0.006	0.005	0.004	0.006	0.008	0.009	0.008	0.007	0.005	0.004	0.007	0.009
16	0.005	0.003	0.003	0.004	0.004	0.004	0.003	0.002	0.003	0.005	0.006	0.005	0.004	0.003	0.003	0.004
17	0.002	0.002	0.001	0.001	0.002	0.002	0.002	0.001	0.001	0.002	0.002	0.003	0.002	0.002	0.002	0.001
18	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
19	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
TOTAL	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000

TABLE 4-6. DISTRIBUTION OF VEHICLE-MILES TRAVELLED BY VEHICLE AGE: LIGHT-HEAVY DUTY VEHICLES

Vehicle Age (Years)	Calendar Year 1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
0	0.253	0.188	0.178	0.167	0.154	0.145	0.138	0.132	0.127	0.122	0.116	0.111	0.108	0.106	0.104	0.102
1	0.251	0.279	0.210	0.190	0.175	0.164	0.155	0.149	0.143	0.139	0.135	0.129	0.126	0.124	0.122	0.121
2	0.252	0.187	0.211	0.161	0.147	0.138	0.131	0.125	0.121	0.118	0.116	0.113	0.110	0.108	0.106	0.105
3	0.185	0.176	0.142	0.168	0.132	0.123	0.117	0.112	0.108	0.106	0.104	0.103	0.101	0.094	0.092	0.092
4	0.024	0.129	0.133	0.112	0.137	0.110	0.104	0.100	0.097	0.094	0.093	0.092	0.092	0.089	0.081	0.080
5	0.014	0.017	0.097	0.105	0.091	0.113	0.092	0.088	0.086	0.084	0.082	0.082	0.081	0.083	0.080	0.070
6	0.005	0.009	0.012	0.076	0.084	0.075	0.095	0.078	0.075	0.074	0.073	0.072	0.072	0.073	0.075	0.071
7	0.006	0.004	0.007	0.010	0.061	0.069	0.062	0.079	0.066	0.064	0.063	0.063	0.063	0.064	0.065	0.068
8	0.003	0.004	0.003	0.005	0.008	0.049	0.056	0.051	0.066	0.055	0.055	0.054	0.054	0.055	0.057	0.059
9	0.001	0.002	0.003	0.002	0.004	0.006	0.039	0.046	0.042	0.055	0.046	0.046	0.046	0.047	0.048	0.050
10	0.001	0.001	0.001	0.002	0.002	0.003	0.005	0.032	0.037	0.035	0.046	0.039	0.039	0.040	0.041	0.042
11	0.001	0.001	0.000	0.001	0.002	0.001	0.003	0.004	0.025	0.030	0.028	0.038	0.032	0.033	0.034	0.035
12	0.001	0.001	0.001	0.000	0.001	0.001	0.001	0.002	0.003	0.020	0.024	0.023	0.031	0.027	0.027	0.029
13	0.001	0.001	0.001	0.000	0.000	0.001	0.001	0.001	0.002	0.002	0.016	0.019	0.018	0.025	0.022	0.023
14	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.001	0.001	0.002	0.013	0.015	0.015	0.020	0.018
15	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.001	0.001	0.010	0.012	0.011	0.016
16	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.001	0.007	0.009	0.009
17	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.005	0.007
18	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.004
19	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
TOTAL	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000

assumption of 6.6 percent replacement rate was based on the average fraction of the overall bus fleet purchases in each of the last ten years, according to the APTA data.

The estimated distribution of bus VMT resulting from these calculations is shown in Table 4-7. Although crude, this represents the best reasonably available data on bus VMT in California by age.

4.3 Projecting Vehicle-Miles Travelled

In order to calculate aggregate emissions, emission factors must be combined with estimates of the transportation activity (vehicle-miles travelled or VMT). Radian developed estimates of VMT by each heavy-duty diesel class, both statewide and for selected critical air-pollution areas. This section describes the development of the VMT estimates used in the model, and presents the end results.

4.3.1 Projected Total VMT, Statewide and In Critical Air Pollution Areas

One object of this study was to estimate the baseline and excess diesel emissions in each critical air-pollution area in California. As a general guideline, critical air-pollution areas were defined as those where the present light-duty vehicle smog check program is now in force, or where it is being seriously considered. Since VMT estimates were available only for counties and air basins, however, we were forced to define these areas along the same lines. The critical areas so defined include three entire air basins (South Coast, San Francisco Bay, and Lake Tahoe), the Sacramento Metropolitan area, and a number of individual counties.

For consistency with ARB's existing emission inventory, Radian relied on ARB projections of total heavy-duty diesel VMT, statewide and in each critical air pollution area. ARB's Technical Services Division provided the current projections of total heavy-duty diesel VMT in the state, broken

TABLE 4-7. DISTRIBUTION OF VEHICLE-MILES TRAVELLED BY VEHICLE AGE: TRANSIT BUSES

Vehicle Age (Years)	Calendar Year 1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
0	0.033	0.033	0.033	0.033	0.033	0.033	0.033	0.033	0.033	0.033	0.033	0.033	0.033	0.033	0.033	0.033
1	0.070	0.065	0.066	0.066	0.066	0.066	0.066	0.066	0.066	0.066	0.066	0.066	0.066	0.066	0.066	0.066
2	0.092	0.070	0.065	0.066	0.066	0.066	0.066	0.066	0.066	0.066	0.066	0.066	0.066	0.066	0.066	0.066
3	0.067	0.092	0.070	0.065	0.066	0.066	0.066	0.066	0.066	0.066	0.066	0.066	0.066	0.066	0.066	0.066
4	0.093	0.067	0.092	0.070	0.065	0.066	0.066	0.066	0.066	0.066	0.066	0.066	0.066	0.066	0.066	0.066
5	0.069	0.093	0.067	0.092	0.070	0.065	0.066	0.066	0.066	0.066	0.066	0.066	0.066	0.066	0.066	0.066
6	0.057	0.069	0.093	0.067	0.092	0.070	0.065	0.066	0.066	0.066	0.066	0.066	0.066	0.066	0.066	0.066
7	0.052	0.057	0.069	0.093	0.067	0.092	0.070	0.065	0.066	0.066	0.066	0.066	0.066	0.066	0.066	0.066
8	0.049	0.052	0.057	0.069	0.093	0.067	0.092	0.070	0.065	0.066	0.066	0.066	0.066	0.066	0.066	0.066
9	0.065	0.049	0.052	0.057	0.069	0.093	0.067	0.092	0.070	0.065	0.066	0.066	0.066	0.066	0.066	0.066
10	0.088	0.065	0.049	0.052	0.057	0.069	0.093	0.067	0.092	0.070	0.065	0.066	0.066	0.066	0.066	0.066
11	0.062	0.088	0.065	0.049	0.052	0.057	0.069	0.093	0.067	0.092	0.070	0.065	0.066	0.066	0.066	0.066
12	0.046	0.062	0.088	0.065	0.049	0.052	0.057	0.069	0.093	0.067	0.092	0.070	0.065	0.066	0.066	0.066
13	0.046	0.031	0.041	0.058	0.043	0.032	0.034	0.038	0.046	0.061	0.044	0.061	0.046	0.043	0.044	0.044
14	0.034	0.031	0.020	0.027	0.038	0.028	0.021	0.023	0.025	0.030	0.041	0.029	0.040	0.031	0.028	0.029
15	0.019	0.022	0.020	0.013	0.018	0.025	0.019	0.014	0.015	0.016	0.020	0.027	0.019	0.026	0.020	0.019
16	0.013	0.012	0.015	0.013	0.009	0.012	0.017	0.012	0.009	0.010	0.011	0.013	0.018	0.013	0.017	0.013
17	0.012	0.013	0.012	0.015	0.013	0.009	0.012	0.017	0.012	0.009	0.010	0.011	0.013	0.018	0.013	0.017
18	0.016	0.012	0.013	0.012	0.015	0.013	0.009	0.009	0.008	0.012	0.009	0.010	0.011	0.013	0.018	0.013
19	0.016	0.016	0.011	0.016	0.018	0.017	0.011	0.000	0.001	0.003	0.009	0.019	0.026	0.029	0.032	0.038
TOTAL	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000

down by air-basin and (within air basins) by county. Where a county overlapped two or more air basins, separate estimates of the diesel VMT in each segment of the county were provided. ARB's projections of heavy-duty diesel VMT are based on estimates of the geographic breakdown in 1983, developed by Pacific Environmental Services (Horie and Rapoport, 1985), and area-specific projections of vehicle registration, developed by the California DMV.

The critical air pollution areas defined by ARB are listed in Table 4-8. Also listed in this table are the geographic segments of the ARB emission inventory which were aggregated to calculate the total VMT. The resulting total VMT for 1983 and for each year from 1985 to 2000 are shown in Table 4-9. These critical air-pollution areas accounted for about 66 percent of statewide total VMT.

4.3.2 Breakdown of VMT by Vehicle Class

The estimated breakdown of total projected heavy-duty diesel VMT by vehicle class was based on estimates developed by Horie and Rapoport (1985), CALTRANS projections, and current "Gross Reports" provided by the California DMV.

Horie and Rapoport estimated the heavy-duty truck VMT by axle class (2-axle, 3-axle, 4-axle, and 5+axle) for California as a whole, and for each county within the state, broken down by rural and urban driving. These axle-class categories were then converted to truck size classes: light-heavy duty (8,500-16,000 lb.), medium-heavy duty (16,001-33,000 lb), and heavy-heavy duty (greater than 33,000 lb.). Horie and Rapoport also estimated the fraction of trucks in each size class which were diesels, and the fraction which were registered outside California.

The classifications used by Horie and Rapoport are not the same as the ones used in this study--we defined the dividing line between light-heavy and medium-heavy at 14,000 lb, and the line between medium-heavy and heavy-heavy duty at 50,000 lb. GVW, corresponding to the division between single-

TABLE 4-8. CRITICAL AIR POLLUTION AREAS INCLUDED IN THE MODEL

Area	ARB Inventory Area
1. California	California
2. South Coast AQMD	South Coast Air Basin
3. Bay Area AQMD	San Francisco Bay Air Basin
4. Metropolitan Sacramento	Sacramento County
	Yolo County
	Sacramento Valley portion of Solano County
	Sacramento Valley portion of Placer County
5. Fresno Metropolitan Area	Fresno County
6. Bakersfield Metropolitan Area	San Joaquin Valley portion of Kern County
7. San Diego Metropolitan Area	San Diego Air Basin
8. Santa Barbara Metropolitan Area	Santa Barbara County
9. Stockton Metropolitan Area	San Joaquin County
10. Ventura Creek	Ventura County
11. Lake Tahoe Basin	Lake Tahoe Air Basin

TABLE 4-9. PROJECTED TOTAL HEAVY-DUTY DIESEL VMT FOR CRITICAL AREAS

	California	South Coast AQMD	Bay Area AQMD	Metro Sacramento	Fresno County	Kern County	San Diego County	San Joaquin County	Santa Barbara County	Ventura County	Lake Tahoe
1983	20,494,219	5,962,305	2,964,883	1,051,317	717,724	1,020,461	879,072	547,444	241,519	347,549	21,273
1985	22,763,410	6,508,332	3,142,779	1,211,585	821,782	1,137,865	1,047,207	660,840	272,709	378,354	22,790
1986	23,701,462	6,740,323	3,260,495	1,269,767	856,077	1,187,557	1,096,800	693,302	281,427	395,006	23,957
1987	24,639,544	6,972,316	3,378,216	1,327,951	890,372	1,237,249	1,146,393	725,764	290,145	411,658	25,124
1988	25,577,623	7,204,308	3,495,933	1,386,135	924,668	1,286,941	1,195,987	758,227	298,863	428,310	26,291
1989	26,515,705	7,436,301	3,613,654	1,444,319	958,963	1,336,633	1,245,580	790,689	307,581	444,962	27,458
1990	27,453,757	7,668,292	3,731,370	1,502,501	993,258	1,386,325	1,295,173	823,151	316,299	461,614	28,625
1991	28,111,677	7,812,493	3,807,288	1,547,747	1,017,323	1,422,404	1,333,310	848,737	321,096	473,773	29,571
1992	28,769,572	7,956,692	3,883,205	1,592,991	1,041,388	1,458,482	1,371,446	874,322	325,894	485,932	30,516
1993	29,427,462	8,100,890	3,959,121	1,638,235	1,065,452	1,494,560	1,409,582	899,907	330,692	498,091	31,461
1994	30,085,357	8,245,089	4,035,038	1,683,479	1,089,517	1,530,638	1,447,718	925,492	335,490	510,250	32,406
1995	30,743,223	8,389,286	4,110,949	1,728,721	1,113,581	1,566,716	1,485,854	951,077	340,287	522,409	33,351
1996	31,476,185	8,546,180	4,193,547	1,780,250	1,140,178	1,606,942	1,529,080	980,299	345,336	535,988	34,443
1997	32,209,115	8,703,075	4,276,138	1,831,777	1,166,774	1,647,167	1,572,306	1,009,521	350,385	549,566	35,533
1998	32,942,047	8,859,969	4,358,730	1,883,304	1,193,370	1,687,393	1,615,532	1,038,744	355,433	563,145	36,623
1999	33,674,977	9,016,864	4,441,321	1,934,831	1,219,966	1,727,618	1,658,758	1,067,966	360,482	576,723	37,713
2000	34,407,881	9,173,755	4,523,910	1,986,356	1,246,562	1,767,843	1,701,983	1,097,188	365,530	590,301	38,803

Source: ARB emissions inventory.

unit and tractor-trailer trucks. Thus, in order to apply their data in the current study, several manipulations were required. First, our study dealt with diesel vehicles only, while the PES estimates included both gasoline and diesel vehicles. Based on PES data, we assumed that 5 percent of the light-heavy, 38 percent of the medium-heavy, and 95 percent of the heavy-heavy truck VMT in both rural and urban operation were accumulated by diesels.

Next, it was necessary to convert from PES' to Radian's classification scheme. Since there are very few diesel trucks between 14,000 and 16,000 lb. GVW, we were able to assume that the the PES and Radian light-heavy duty classes were the same. The PES heavy-heavy class, however, includes a number of single-unit trucks that are classed as medium-heavy by Radian. To convert to Radian's classification, we assumed (based on data from the U.S. Census Bureau's Truck Inventory and Use Survey) that 30 percent of the PES heavy-heavy class California trucks and 5 percent of the PES heavy-heavy out-of-state trucks were single-unit vehicles, and thus classed as medium-heavy.

Since the basic PES data were supplied by slightly different weight classes, the total to diesel VMT conversion was done first and the weight class conversions were assumed to have a roughly neutral effect. For the total to diesel DVMT conversion all PES light HDV vehicles (and hence almost all gas vehicles) belong to the Radian light HDV class. The PES medium HDV's will be mostly diesel and go to the primarily diesel medium Radian HDV class. The PES heavy HDV's are 95 percent diesel, and are split between Radian's medium-heavy class (which is mostly diesel) and its heavy-heavy class (which is entirely diesel). Since the diesel engined trucks are predominant at the medium/heavy boundary, whether this boundary occurs at 33,000 or 50,000 lbs. was not deemed to have a significant impact on the results.

Up to this point, all of the data applied only to the PES base year of 1983. To estimate the VMT breakdown in future years, Radian relied on CALTRANS projections of future statewide registrations and VMT for three classes of diesel vehicles, roughly corresponding to our light-heavy, medium-heavy, and heavy-heavy classes. The breakdown of VMT by class in future years was estimated by calculating the ratio of CALTRANS-projected VMT for that class in the future year to CALTRANS-estimated VMT in 1983. The PES estimate of VMT for that class in 1983 was then multiplied by this ratio.

The result of these calculations was a six-way division of estimated total heavy-duty diesel VMT in each region in the base year, 1983, and for future years. VMT were divided into heavy-heavy, medium-heavy, and light-heavy, and within each group, by in-state vs. out-of-state vehicles. For our purposes, however, it was necessary to estimate the fraction of in-state VMT provided by Federal vs. California engines, and to estimate transit bus VMT separately from other medium-heavy vehicles.

Urban bus DVMT data were obtained from the "California Transit Energy Demand Model" prepared for the California Energy Commission, Technology Assessment Project Office (SYDEC, 1983). The SYDEC report provided urban bus VMT (among other things) based upon the major urban transit systems in each CalTrans region. These transit systems have the major share of all urban bus travel, and other urban bus VMT was assumed to grow at the same rate. By matching the urban transit districts with the counties in each region, it was possible to assign all or part of VMT for each transit district to a county. If a district covered more than one county this was stated and the VMT was proportioned. The difference between the transit district totals for a region and the regional total was taken, and this VMT was proportioned between the counties without transit districts, based upon the urban truck VMT already known. Counties with no urban truck VMT were assumed to have no urban transit bus VMT.

Once the urban bus VMT for each county was known, this mileage could be subtracted from the appropriate truck VMT category. Intracity buses fall in the medium HDV size category (16,000 to 50,000 lbs.). Making these changes in the data gave the estimated VMT by county for in-state and out-of-state vehicles, divided by vehicle class.

To estimate the fraction of in-state VMT contributed by vehicles with Federal engines, Radian estimated the fraction of each class of each class of California registered vehicles equipped with Federal engines. For urban buses, we relied on work by a previous ARB contractor (Crawford et al., 1985), who observed several hundred buses in the field, then obtained engine data (including year and Federal or California certification) for each. Of the buses surveyed which had been built when California standards were in effect, some 32 percent were equipped with Federal engines, and 68 percent with California engines. VMT by the two classes were assumed to be similarly divided.

This large percentage of Federal engines in buses is due partly to the purchase of used buses from out-of-state, and partly to the fact that, from 1982 to 1984, transit districts were permitted to buy buses equipped with Federal engines. This exemption has now expired, so that the fraction of buses with Federal engines can be expected to decline somewhat in the future. Thus, by assuming a constant VMT fraction for Federal-engined buses, we may be overestimating NO_x and under-estimating PM emissions to a slight degree. The point becomes moot after 1989, however, as 1990 and later standards are the same for both California and Federal engines.

For the other three vehicle classes, Radian relied on DMV's periodic "Gross Reports" to estimate the fraction of Federal engines. A heavy-duty vehicle with a Federal engine may be registered in California under two circumstances: if it was brought in used, or if it is registered under the IRP program. According to the Gross Reports, approximately 27 percent of heavy-heavy tractors are registered under the IRP program, while a negligible fraction of the other classes are so registered.

The Gross Reports also provide data on the initial California registrations of new vehicles and out-of-state vehicles, broken down by body type. Since new vehicles must have California engines, while out-of-state vehicles almost certainly have Federal engines, the ratio of these two numbers provides some indication of the fraction of Federal engines in the fleet.

For the tractor body type, new vehicle registrations and registrations of out-of-state vehicles are about equal, suggesting that vehicles with Federal engines could make up at least 50 percent of the total fleet, even ignoring the IRP vehicles. For typical medium-heavy body types (e.g., flatbed, dump), out-of-state registrations are about 32 percent of the total, while for typical light-heavy body types (e.g., vans) they are about 17 percent.

These numbers may overstate the actual VMT due to Federal engines somewhat. First, some incoming used vehicles may originally have been purchased in California, and may thus have California engines. Since they are already used, the incoming used vehicles may also have a shorter remaining lifespan, and thus contribute a less-than-proportional amount to total VMT. They may also be more likely to move back out of state. These considerations were assumed to reduce the VMT fraction supplied by Federal engines by about one-third from the values in the preceding paragraph. For heavy-heavy vehicles, this was offset by the new California vehicles allowed to register under the IRP, however. The resulting estimated VMT fractions for Federal vehicles are: heavy-heavy, 50 percent; medium-heavy, 17 percent; and light-heavy, 11 percent. These were assumed not to change in future years.

Table 4-10 shows the resulting projections of heavy-duty diesel VMT by vehicle class for California as a whole, while Table 4-11 shows the same data for the South Coast AQMD. VMT projections for the other critical air pollution areas covered in the model are given in the Appendix.

TABLE 4-10. ESTIMATED ANNUAL VMT BY YEAR AND VEHICLE CLASS STATEWIDE

Calendar Year	California Registered-California Engines				California Registered-Federal Engines				Out-of-State Registered Federal Engines			Total All Classes
	Light	Medium	Heavy	Buses	Light	Medium	Heavy	Buses	Light	Medium	Heavy	
1983	328,351	4,587,434	4,548,965	535,088	40,583	1,219,445	4,548,965	251,806	11,410	1,528,367	2,893,807	20,494,219
1985	802,009	5,085,222	4,691,902	586,845	99,125	1,351,768	4,691,902	276,162	27,507	1,832,430	3,318,537	22,763,410
1986	1,009,218	5,246,774	4,894,810	575,089	124,735	1,394,712	4,894,810	270,630	33,586	1,884,046	3,373,052	23,701,462
1987	1,194,696	5,454,006	5,085,129	568,961	147,659	1,449,799	5,085,129	267,746	39,061	1,915,097	3,432,261	24,639,544
1988	1,365,567	5,607,107	5,304,096	566,496	168,778	1,490,497	5,304,096	266,586	44,137	1,963,494	3,496,767	25,577,623
1989	1,529,416	5,810,883	5,460,853	566,367	189,029	1,544,665	5,460,853	266,526	49,463	2,038,589	3,599,060	26,515,705
1990	1,678,086	6,029,091	5,625,819	565,852	207,404	1,602,670	5,625,819	266,283	54,458	2,108,734	3,689,541	27,453,757
1991	1,804,927	6,188,851	5,736,067	561,086	223,081	1,645,138	5,736,067	264,041	58,507	2,154,424	3,739,489	28,111,677
1992	1,923,926	6,348,711	5,851,025	558,203	237,789	1,687,632	5,851,025	262,684	62,283	2,195,090	3,791,205	28,769,572
1993	2,035,411	6,507,267	5,969,984	557,073	251,568	1,729,780	5,969,984	262,152	65,812	2,233,862	3,844,571	29,427,462
1994	2,139,956	6,667,338	6,097,042	557,461	264,489	1,772,330	6,097,042	262,334	68,601	2,265,810	3,892,955	30,085,357
1995	2,241,730	6,865,023	6,170,689	562,137	277,068	1,824,879	6,170,689	264,535	71,779	2,315,953	3,978,741	30,743,223
1996	2,347,844	7,050,713	6,313,385	570,907	290,183	1,874,240	6,313,385	268,662	81,588	2,349,042	4,016,236	31,476,185
1997	2,432,053	7,209,841	6,454,523	576,946	300,59[illegible]	1,916,540	6,454,523	271,504	84,515	2,402,057	4,106,020	32,209,115
1998	2,516,212	7,378,068	6,590,497	582,392	310,993	1,961,259	6,590,497	274,067	87,439	2,458,104	4,192,519	32,942,047
1999	2,593,542	7,541,342	6,726,640	598,297	320,550	2,004,661	6,726,640	281,552	90,127	2,512,501	4,279,126	33,674,977
2000	2,667,941	7,698,404	6,868,966	612,164	329,746	2,046,411	6,868,966	288,077	92,712	2,564,828	4,369,666	34,407,881

TABLE 4-11. ESTIMATED ANNUAL VMT BY YEAR AND VEHICLE CLASS FOR THE SOUTH COAST AQMD

Calendar Year	California Registered-California Engines				California Registered-Federal Engines				Out-of-State Registered Federal Engines			Total All Classes
	Light	Medium	Heavy	Buses	Light	Medium	Heavy	Buses	Light	Medium	Heavy	
1983	136,108	1,283,028	1,301,142	283,987	16,822	341,058	1,301,142	133,641	4,730	429,515	731,130	5,962,305
1985	323,870	1,385,547	1,307,393	303,419	40,029	368,310	1,307,393	142,785	11,108	501,676	816,802	6,508,332
1986	404,432	1,418,643	1,353,513	295,069	49,986	377,108	1,353,513	138,856	13,459	511,867	823,878	6,740,323
1987	475,476	1,464,556	1,396,492	289,922	58,767	389,312	1,396,492	136,434	15,546	516,733	832,588	6,972,316
1988	540,062	1,496,197	1,447,462	286,850	66,749	397,723	1,447,462	134,988	17,456	526,459	842,900	7,204,308
1989	601,464	1,541,863	1,481,870	285,174	74,338	409,862	1,481,870	134,199	19,452	543,524	862,684	7,436,301
1990	656,634	1,591,772	1,519,010	283,491	81,157	423,129	1,519,010	133,408	21,309	559,417	879,955	7,668,292
1991	702,079	1,624,263	1,539,594	279,437	86,774	431,766	1,539,594	131,500	22,758	568,149	886,579	7,812,493
1992	744,161	1,656,853	1,561,623	276,439	91,975	440,429	1,561,623	130,089	24,091	575,620	893,789	7,956,692
1993	783,086	1,689,178	1,584,878	274,408	96,786	449,022	1,584,878	129,133	25,320	582,664	901,537	8,100,890
1994	819,126	1,721,941	1,610,389	273,204	101,240	457,731	1,610,389	128,567	26,259	587,996	908,247	8,245,089
1995	853,938	1,764,432	1,621,968	274,166	105,543	469,026	1,621,968	129,019	27,343	598,105	923,778	8,389,286
1996	889,031	1,801,359	1,649,588	276,784	109,880	478,842	1,649,588	130,251	30,894	603,036	926,927	8,546,180
1997	916,296	1,832,771	1,678,002	278,308	113,250	487,192	1,678,002	130,969	31,842	613,551	942,893	8,703,075
1998	943,456	1,866,537	1,705,132	279,587	116,607	496,168	1,705,132	131,570	32,785	624,855	958,138	8,859,969
1999	967,699	1,898,521	1,731,852	285,819	119,603	504,670	1,731,852	134,503	33,628	635,562	973,153	9,016,864
2000	990,904	1,929,193	1,760,403	291,106	122,471	512,823	1,760,403	136,991	34,434	645,830	989,196	9,173,755

5.0 ESTIMATING THE FREQUENCY OF OCCURRENCE OF EMISSIONS-RELATED DEFECTS

Estimating the frequency of occurrence of emissions-related defects in heavy-duty trucks in California was both a very critical and a very difficult task. Reliable broad-based statistical data on the incidence of emissions defects in heavy-duty diesel vehicles do not exist. Obtaining such data would require the equivalent of a roadside inspection program for heavy-duty vehicles. Since some of the measurements required involve invasive procedures, such an inspection program would be very difficult and expensive to accomplish. It would also raise troublesome questions about the possible introduction of defects in the process of inspecting for them (a problem which has been termed "iatrogenic maintenance"). While it is recommended that such a program be conducted in the future, it was beyond the scope of the present study.

In order to obtain some quantitative data on the incidence of emissions defects in heavy-duty diesel trucks in California, two surveys were undertaken.

1. A questionnaire survey of heavy-duty diesel engine mechanics, rebuilders, and fleet maintenance managers, asking them to estimate the frequency of occurrence of specific defects in the truck fleet. Survey questions on this topic were developed by Radian, but the survey itself was conducted by another ARB contractor (Sierra Research, 1987). The results of this survey are presented in Section 5.1 below.

2. A visual survey by Radian of truck smoke opacity in California. This survey is described in Section 5.2 below.

The results of these surveys were highly surprising, in that they contradict much of the conventional wisdom about heavy truck maintenance and operating characteristics. Many observers involved in heavy-duty emissions issues, including the authors, had believed that heavy-heavy trucks were maintained extremely well as a matter of economic necessity, and that the incidence of defects in this group (aside, perhaps, from problems such as tampering with the puff limiter) would consequently be fairly small. As the data in Sections 5.1 and 5.2 make clear, this is not the case.

In addition to the two surveys undertaken in this project, a number of quantitative, semi-quantitative, and qualitative data-sources are available which have some relevance to the problem. The more significant of these include the following.

- A visual survey of bus acceleration smoke conducted for the ARB by Sierra Research (Crawford et al., 1985).

- Data on emissions tests and maintenance/tampering problems for a sample of 31 in-use heavy-duty engines developed in a joint program by EPA and the Engine Manufacturer's Association (EMA, 1985). In addition to the data presented by EMA, we contacted each manufacturer individually. Four of the five participants were able to provide us with additional information on the maintenance status of each of their engines tested (Sienicki, 1986; Schwochert, 1985; Dowdall, 1985; Jorgensen, 1986). These data are given in the Appendix.

- Data, in a similar form to the EPA/EMA data discussed above, for a sample of fourteen Cummins engines recalled as part of a Cummins internal study (Jorgensen, 1986), and provided to us by Cummins.

- A survey of heavy-duty maintenance and rebuild practices commissioned by the Engine Manufacturer's Association (Survey Data Research, 1981).

- Qualitative data and impressions obtained through discussions with heavy-duty diesel mechanics, fleet maintenance managers, manufacturer personnel concerned with engine maintenance, and many other knowledgeable parties.

- Data on the incidence of maintenance and especially tampering problems in light-duty vehicles, obtained through Radian's work in evaluating I&M programs for those vehicles. These data are useful mostly as a qualitative indication of the tendencies toward various types of tampering.

5.1 Survey of Diesel Mechanics and Engine Rebuilders

Hard statistical data on the relative frequency of emissions-related defects for heavy duty diesel engines are not available. However, experienced professional mechanics and other engine professionals would be expected to have a reasonably good picture of the state of maintenance of the "average" truck. Where hard statistical data are lacking, the consensus of those directly involved in the field may be a useful guide; this is the foundation of the so-called "Delphi" method.

In order to obtain some guidance as to the frequency of the various emissions-related defects listed in Section Three, Radian prepared a set of questions to be included in a survey of diesel engine mechanics and rebuilders which was being conducted by another ARB contractor. Radian's contribution to this questionnaire is given in the Appendix. A total of 103 responses to this survey were received. The conduct of the survey itself is described in the other contractor's final report (Sierra Research, 1987).

The list of questions given in the Appendix was based on a preliminary version of the list of emissions-related defects developed in Section Three. The respondents were asked to estimate (or give their best guess at) the fraction of all trucks on the road exhibiting each of a number of types of problems such as fouled injectors, clogged air filters, etc. Respondents were asked to estimate these frequencies separately for line-haul trucks, other trucks with turbocharged engines, and trucks with naturally-aspirated engines.

The wording of the survey represented a compromise. From the standpoint of survey response and reliability, it would have been preferable to ask about the incidence of problems in the particular group of trucks that each respondent was responsible for, since respondents could then have answered from their own knowledge rather than from their (possibly less reliable) impressions of the industry as a whole.

On the other hand, the survey was planned to target mostly fleet maintenance managers. Asking about only their own fleets would have biased the estimates downward, since the very existence of a fleet maintenance manager implies a significant commitment to proper maintenance. In addition, a maintenance manager's job is to keep the incidence of defects in the fleet as low as possible; this was also expected to bias their estimates of defect frequency in their own fleets. Many of the practices asked about are also illegal, and it was considered likely that respondents would be unwilling to admit to engaging in illegal acts. For all of these reasons, it was considered necessary to ask the questions in the vaguer and less definite form applying to trucks as a group.

The results of this survey are summarized in Table 5-1. This table shows the minimum, maximum, and median, the sample mean, and the upper and lower confidence limits (at plus or minus one standard deviation, giving a 68 percent confidence level) for the responses to each question. As this table indicates, there was considerable scatter in the responses. Estimates of the fraction of smoke limiters reset in line-haul trucks, for example, ranged from 0 to 100 percent! Most of the responses were less extreme, however--tending to cluster in a band extending 10 percent or so on each side of the mean, as indicated by the fairly narrow range of the confidence limits.

TABLE. 5-1. SURVEY OF DIESEL MECHANICS AND MAINTENANCE MANAGERS: QUESTIONNAIRE RESULTS

Question	Minimum	Lower Con. Limit	Sample Mean	Upper Con. Limit	Maximum	Median
1. Injection Timing Advanced						
Line Haul	0	11.1	12.4	13.8	50	10
Other Turbocharged	0	7.3	8.6	9.9	50	5
Nat. Aspirated	0	9.8	11.7	13.5	75	10
2. Injection Timing Retarded						
Line Haul	0	6.5	7.6	8.6	30	5
Other Turbocharged	0	5.6	5.8	8.1	40	2
Nat. Aspirated	0	5.1	6.2	7.3	45	3
3. Injectors-Worn or Clogged						
Line Haul	0	17.8	20.0	22.1	75	15
Other Turbocharged	0	18.9	21.1	23.2	75	15
Nat. Aspirated	0	20.1	22.4	24.6	75	20
4. Smoke-Limiter Reset						
Line Haul	0	25.8	28.8	31.9	100	20
Other Turbocharged	0	15.2	17.7	20.3	80	10
5. Smoke-Limiter Disabled						
Line Haul	0	26.8	29.8	32.9	100	25
Other Turbocharged	0	15.0	17.4	19.8	80	10
6. Maximum Fuel "Turned Up"						
Line Haul	0	21.8	23.7	25.7	80	20
Other Turbocharged	0	12.3	14.1	15.9	80	10
Nat. Aspirated	0	15.1	17.2	19.3	90	10
7. Air Filter Clogged						
Line Haul	0	20.0	21.9	23.9	80	20
Other Turbocharged	0	21.1	23.2	25.3	65	20
Nat. Aspirated	0	19.0	21.0	23.1	60	18
8. Intercooler Clogged						
Line Haul	0	5.9	7.0	8.0	60	5
Other Turbocharged	0	3.4	4.1	4.9	20	1
9. Turbocharger Worn						
Line Haul	0	12.3	13.7	15.2	80	10
Other Turbocharged	0	11.6	13.2	14.8	80	10
10. Nonstandard Turbocharger						
Line Haul	0	7.5	8.7	9.9	50	5
Other Turbocharged	0	5.0	5.8	6.6	25	5
11. Pressure Leaks						
Line Haul	0	11.6	12.8	14.0	50	10
Other Turbocharged	0	10.5	11.9	13.3	60	10
12. Excessive Backpressure						
Line Haul	0	5.3	6.5	7.7	15	5
Other Turbocharged	0	5.6	6.9	8.2	15	10
Nat. Aspirated	0	6.2	8.4	10.7	25	10

Total responses: 103

The data in Table 5-1 support the impressions gathered from anecdotal evidence and review of trucking trade magazines, and are consistent with the results of the visual smoke survey described in Section 5.2. Resetting and disabling smoke limiters, increasing maximum fuel settings, and advancing the injection timing are considered to be quite common, especially on line-haul trucks. The most common maintenance problems are worn or clogged injectors and clogged air filters, followed by worn turbochargers and pressure leaks. Clogged intercoolers and excessive backpressure are considered less common, but by no means rare.

5.2 Visual Survey of Truck Smoke Emissions

In the process of developing the list of emission-related defects presented in Section Three, it was determined that most of the more common types of emissions-related defects show a characteristic smoke emissions "signature". Smoke emissions in different operating modes are different for different types of defects. For example, tampering with the puff limiter on a turbocharged engine results in excess smoke during acceleration, but has no effect on steady-state smoke. Along the same lines, increasing the fuel rate on a naturally-aspirated engine increases smoke opacity at full power, whether in acceleration or steady-state, but has no effect on smoke density at normal road-load power. Thus, the results of smoke opacity observations in different operating modes can be used to estimate the frequency of occurrence of specific defects. In order to obtain first-hand information on diesel truck smoke emissions patterns, Radian undertook a visual survey of truck smoke emissions in California.

5.2.1 Survey Procedure

Truck smoke emissions were observed visually, using an ARB-certified smoke reader, and also recorded photographically. The smoke reader was Richard Welsh, then of Radian's staff. In order to gain ARB certification, a smoke reader must pass an ARB-administered test demonstrating his ability to correctly estimate the opacity of a smoke plume by visual observation. His observations are subsequently admissible as evidence in court. The technique is thus reasonably accurate, although it is based on nothing but the human eye.

Trucks were observed in three operating modes: acceleration from low speed or stop, steady-state full-power operation (up a steep hill), and steady-state road-load operation on a level section of freeway. Most acceleration-mode observations were made at California Highway Patrol truck weigh stations, with the permission of the CHP. Some observations were also taken at stop-lights in areas of heavy truck traffic. Full-power observations were made at convenient sites on freeways or elsewhere where trucks could be observed climbing a moderate-to-steep hill. Road-load observations were made only on flat stretches of freeway, during periods of uncongested traffic.

Observations were made at a number of sites in the Los Angeles and Oakland/Sacramento areas; in all, 1,234 observations at 13 locations were taken. An attempt was made to observe a representative cross-section of the trucking activity in the State (e.g., long-distance and interstate trucking on I-80, short-distance trucking on L.A.'s Harbor Freeway and the L.A. harbor area). The full-load and acceleration-mode results may have been biased upward somewhat by the decision to include observations at L.A. harbor (which has a high concentration of smoky trucks) in these categories. However, the type of short-haul trucking observed at L.A. harbor is not uncommon in California, and would otherwise have been under-represented (since short-haul trucks often do not travel on freeways).

Due to the difficulty of gaging the opacity of the exhaust plume under a vehicle, all of the smoke opacity observations were made on trucks with vertical exhaust stacks. The vast majority of these trucks were in the heavy-heavy class. So, also, were the vast majority of trucks which could confidently be identified as diesels. The survey data are thus directly applicable only to this class of trucks.

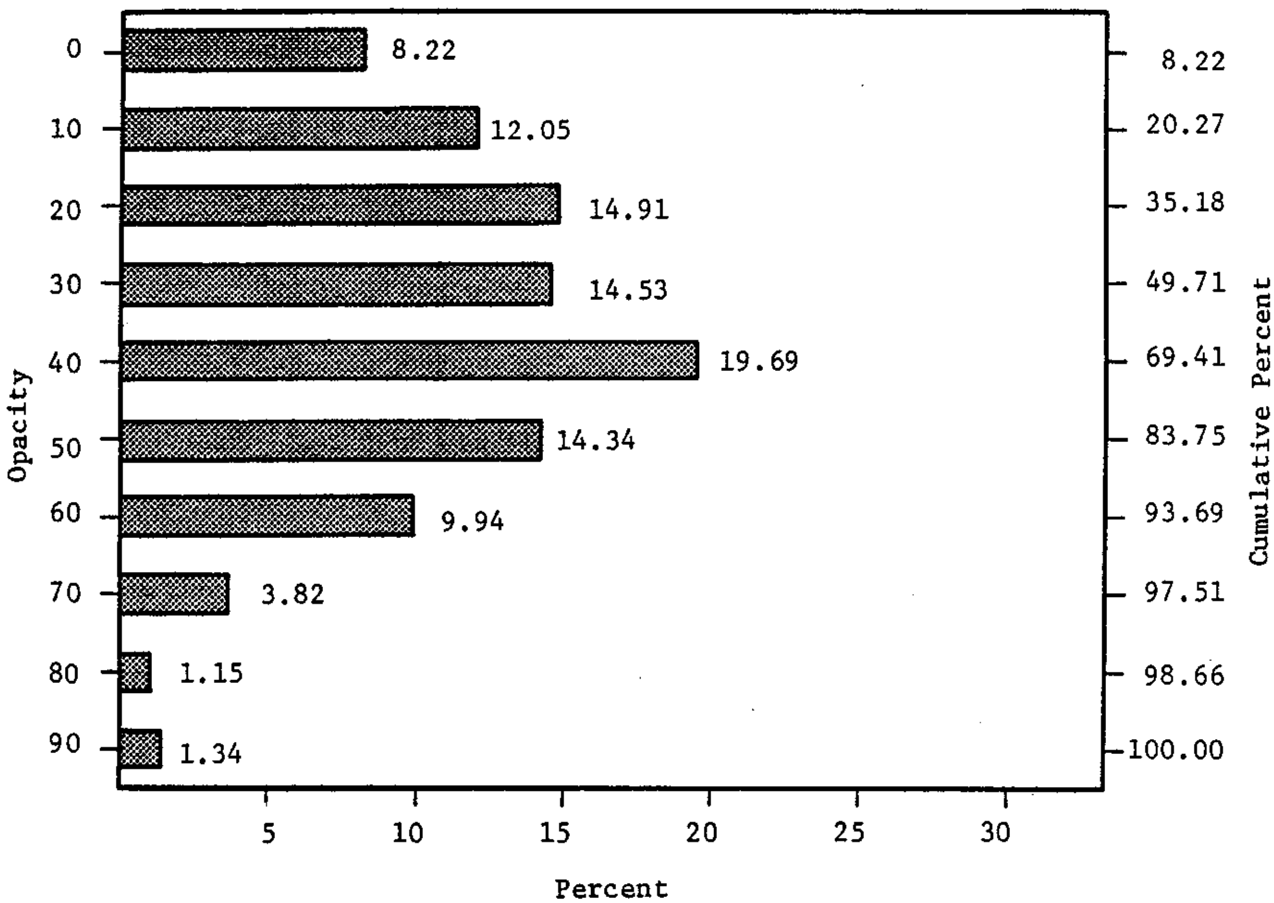
Other limitations to the survey include our inability to control the observing conditions, since we were limited in our access to the freeways and could not always obtain ideal sun direction and wind and cloud conditions. In addition, the smoke plumes from the stacks spread out some as they left the stack (which would increase the optical path length somewhat), and were quickly dissipated by the wind from the truck's motion. Our data are thus not equivalent to those which would be measured by an opacimeter in the truck's exhaust stack. The similarities are sufficient, however, to permit a qualitative comparison of these results with those of the Federal smoke opacity certification tests.

5.2.2 Results and Discussion

Figures 5-1 through 5-3 present the results of the truck smoke survey. Figure 5-1 shows the distribution of smoke opacities observed for trucks during transient accelerations from a stop. Figure 5-2 shows the opacity distribution for steady-state, full-load operation, and Figure 5-3 shows the opacity distribution for steady-state, road-load operation.

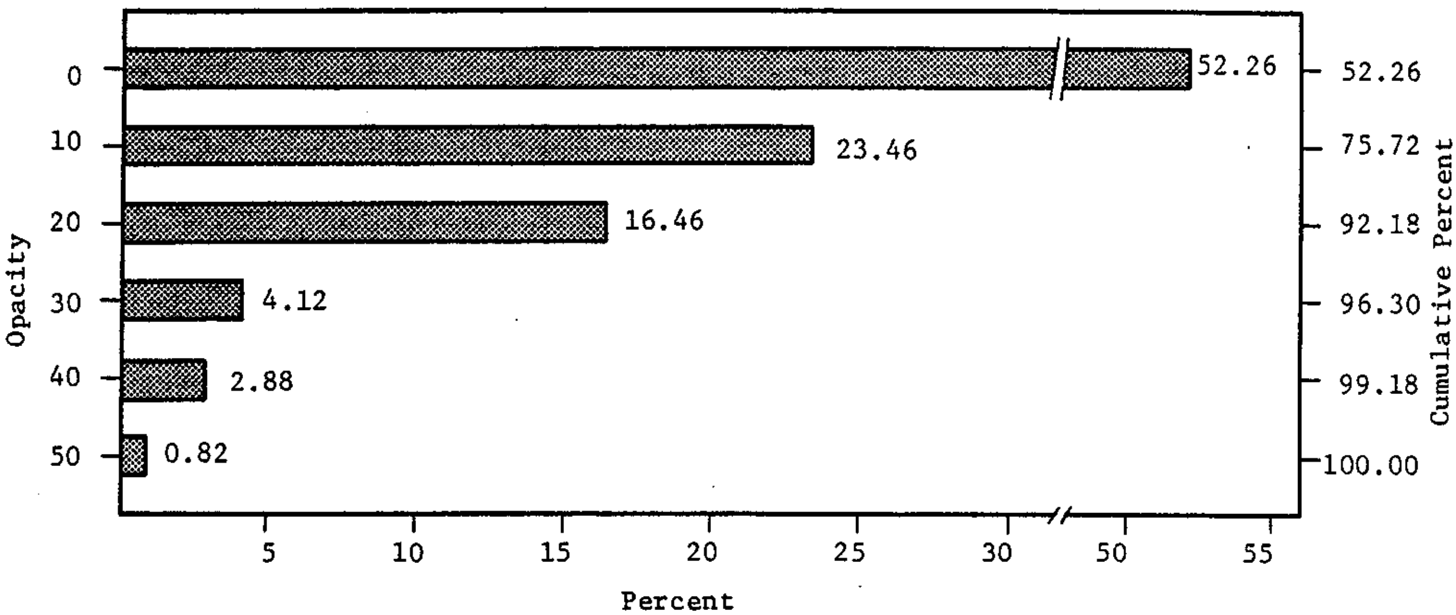
For comparison, Table 5-2 lists the minimum, maximum, and mean smoke opacities for new engines from the Federal Smoke Certification test for a number of years. Lug-down and average acceleration smoke opacity data are presented for 1972, 1973, 1980, and 1985; while acceleration peak opacities are given for 1980 and 1985 (this test mode was only introduced in 1974). Only the data for the five major U.S. manufacturers are included, since these five account for virtually all heavy-heavy trucks on the road.

The acceleration smoke observations in our survey are probably most comparable to the acceleration peak opacity values from the Federal certification data. However, due to the eye's tendency to "average out" rapid changes in opacity, we would expect the visual survey results to be somewhat lower than the Federal "peak" value, falling somewhere between the "peak" and the averaged "acceleration" value. Comparison of Table 5-2 with Figure 5-1, however, shows a much higher average smoke opacity in our visual survey.



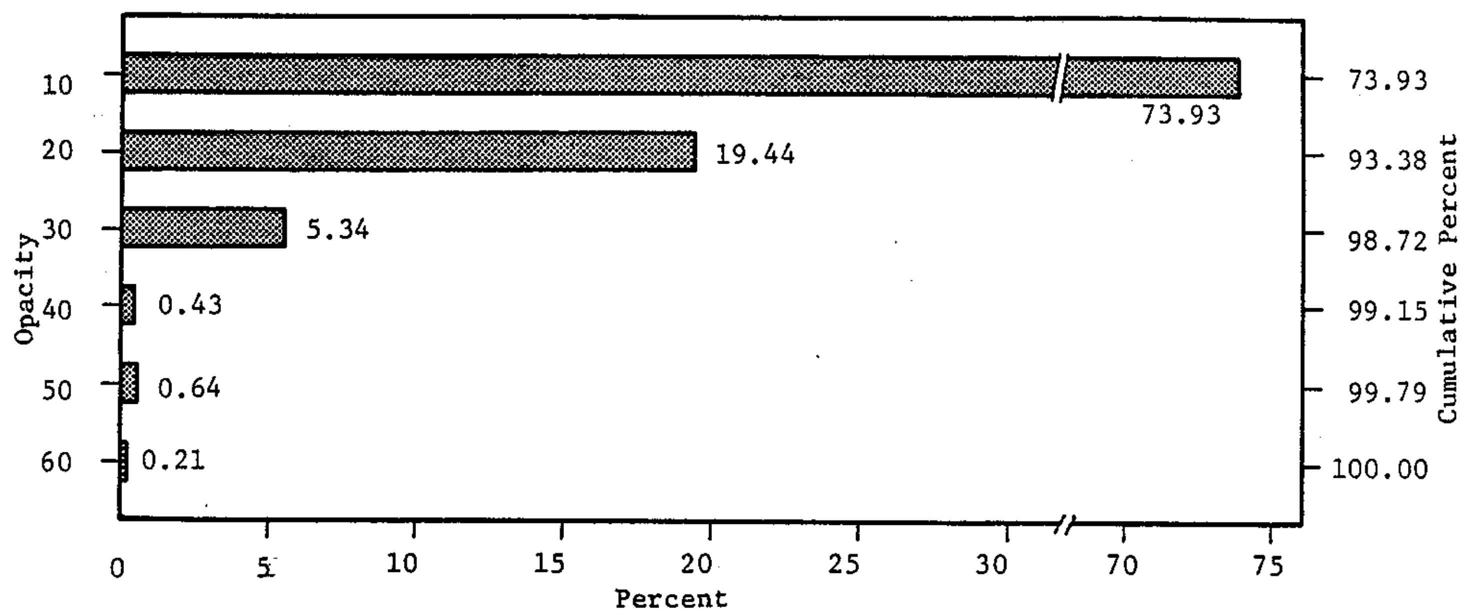
Sample size = 523

Figure 5-1. Distribution of Truck Smoke Opacity Under Transient Acceleration



Sample size = 243

Figure 5-2. Distribution of Truck Smoke Opacity in Full-Power, Steady-State Operation



Sample size = 468

Figure 5-3. Distribution of Truck Smoke Opacity in Road-Load Operation

TABLE 5-2. HEAVY-DUTY DIESEL ENGINE SMOKE EMISSIONS FROM THE FEDERAL SMOKE OPACITY CERTIFICATION TEST+

	Opacity (%)		
	Min.	Mean	Max.
ACCELERATION MODE:			
Naturally Aspirated			
Federal 1972	1.4	10.9	26.4
Federal 1973	1.2	10.8	26.4
California 1980	8.0	8.0*	8.0
Federal 1980	2.0	8.7	17.0
California 1985	9.0	12.1	16.6
Federal 1985	4.9	11.0	18.8
Turbocharged			
Federal 1972	5.6	19.2	37.3
Federal 1973	6.7	17.2	35.6
California 1980	6.0	14.5	20.0
Federal 1980	6.0	13.0	20.0
California 1985	10.2	14.9	18.1
Federal 1985	3.7	13.5	19.2
LUG-DOWN MODE:			
Naturally Aspirated			
Federal 1972	1.0	8.5	17.8
Federal 1973	1.3	8.5	16.6
California 1980	9.0	9.0*	9.0
Federal 1980	1.0	7.9	15.0
California 1985	6.5	11.1	13.7
Federal 1985	4.4	10.5	13.2
Turbocharged			
Federal 1972	1.0	5.2	13.3
Federal 1973	1.2	5.0	15.2
California 1980	3.0	7.4	11.0
Federal 1980	1.0	6.2	14.0
California 1985	6.2	9.1	11.8
Federal 1985	0.8	5.8	13.5

* One engine only.
+ Includes Caterpiller, Cummins, Detroit Diesel, Navistar (International Harvester), and Mack engines only.

Source: U.S. EPA Certification Test Results.

TABLE 5-2. (Continued)

	Opacity			No. Engines Over		
	Min.	Mean	Max.	35%	40%	No. Engines
PEAK MODE:						
Naturally Aspirated						
Federal 1980	5.0	14.6	40.0	1	0	18
California 1980	11.0	11.0	11.0	0	0	1
Federal 1985	11.4	23.1	36.8	2	0	7
California 1985	15.2	20.0	25.7	0	0	3
Turbocharged						
Federal 1980	7.0	18.4	39.0	2	0	32
California 1980	9.0	23.7	41.0	1	1	12
Federal 1985	6.1	24.3	47.5	7	1	34
California 1985	11.6	23.1	32.6	0	0	12

* One engine only.
\+ Includes Caterpiller, Cummins, Detroit Diesel, Navistar (International Harvester), and Mack engines only.

Source: U.S. EPA Certification Test Results.

Figure 5-1 shows that more than half the trucks observed had acceleration smoke opacity of 40 percent or greater, with about a sixth having opacities of 60 per cent or more. In contrast, only one engine family in each of model years 1980 and 1985 had a certification "peak" opacity in excess of 40 percent, and the mean values for each year are in the teens and low 20s.

Comparison of the full-power smoke data from our survey with the lug-down mode data from the Federal tests gives a similar result. From a technical standpoint, the lug-down data would be expected to show higher opacities than our full-power data, since most of the engines we observed would not be operating in the lugging mode, but further up the power curve where smoke levels are lower. However, the maximum lug-down smoke shown on the Federal tests is only 15 percent (in 1980), while the means range from 5 percent to 11 percent. Figure 5-2 shows that 16 percent of the trucks in our survey had smoke opacities of around 20 percent, and nearly 8 percent of the trucks significantly exceeded this level.

From an emissions standpoint, the road-load mode is the most important one, since road load is the normal operating mode for most trucks. Problems causing excess emissions in this mode are likely to cause them in all other operating modes as well, and thus have a much greater effect than those problems which increase emissions only in full load or acceleration modes. The exhaust plume from a properly functioning diesel truck in steady part-load operation should have an opacity of a few percent at most (that is, it would fall in the zero percent opacity category in our survey). As Figure 5-3 shows, more than 26 percent of the trucks exceeded this level, with more than 6 percent of the trucks emitting at 20 percent opacity or more. This amount of smoke in steady-state, part-load operation indicates a significant deterioration in the engine combustion process.

In comments on a previous draft of this report, the Engine Manufacturers Association has stated that some trucks could have been experiencing full-power operation even in the steady-state, level freeway operating conditions in which our road-load observations were taken. As a result, it was argued, the appropriate comparison for these data is with lug-down opacity values, rather than part-load values. This assertion is simply not credible. A typical loaded heavy-heavy duty truck uses about 40 to 65 percent of its maximum power to maintain speed at 55 MPH. A truck which required full engine power to maintain its speed in 55 MPH, level road conditions would be so grossly underpowered that it would be unable to maintain speed on even a slight hill, or to accelerate onto a freeway. While it is conceivable that a few of the trucks observed were in fact so underpowered, it is inconveivable that these could make up any significant fraction of the total.

5.3 Estimates of Defect Frequency

In this section, we present our estimates of the frequency of occurrence of significant emissions-related defects in the heavy-duty truck fleet, together with the reasoning behind these estimates. Estimates were developed separately for model years 1960-1987, 1988-1990, 1991-1993, and 1994-2000, to reflect the technological changes resulting from the 1988, 1991, and 1994 emissions standards. Separate estimates were also prepared for each class of heavy-duty vehicles (light-heavy, medium-heavy, heavy-heavy, and transit bus), and for the three possible combinations of registration and engine certification available (California/California, California/Federal, and Out-of-state/Federal).

Future emission controls--To estimate the frequency of emissions control tampering and malfunctions for vehicles in future model years, it was necessary to estimate the incidence of specific emission controls in each model year. The estimates used are shown in Table 5-3. These are based on the results of another project for ARB (Weaver and Klausmeier, 1987), in which Radian characterized the current state of the art of diesel emissions control, and assessed the feasibility of more stringent emissions standards. This project included meetings with every major U.S. diesel manufacturer, as well as most foreign manufacturers who import heavy-duty diesels to this country.

TABLE 5-3. ASSUMED PENETRATION OF EMISSION CONTROL TECHNOLOGIES

	Percent of Vehicles			
	1960-87	1988-90	1991-93	1994-2000
<u>Electronic Timing and Governors</u>				
Heavy-Heavy	0	30	100	100
Medium-Heavy	0	30	100	100
Light-Heavy	0	20	100	100
Transit Bus	0	80	100	100
<u>Catalytic Converters</u>				
Heavy-Heavy	0	0	40	0
Medium-Heavy	0	0	50	0
Light-Heavy	0	0	50	0
Transit Bus	0	0	0	0
<u>Trap-Oxidizers</u>				
Heavy-Heavy	0	0	10	100
Medium-Heavy	0	0	30	100
Light-Heavy	0	0	50	100
Transit Bus	0	0	100	100
<u>Exhaust Gas Recirculation</u>				
Heavy-Heavy	0	0	0	0
Medium-Heavy	0	0	10	20
Light-Heavy	0	0	20	30
Transit Bus	0	0	0	0

Due to the rapid developments in diesel engine technology, as well as the potential for regulatory changes, the estimates shown in Table 5-3 should be considered as only one possible scenario for future heavy-duty diesel emission controls. The reality may turn out to be very different, especially for model years beyond 1991. Widespread use of methanol engines, for instance, could significantly affect the penetration of trap-oxidizers and other particulate control measures. It seems clear, however, from all available data, that some types of emission controls will unquestionably be required in 1991 and subsequent model years, and that these controls will thus be susceptible to tampering and/or malfunction.

Limitations--Developing the estimates presented in this section has called for extensive use of considered engineering judgement, informed by data from all of the sources discussed above. The resulting estimates are necessarily somewhat subjective, but they are based on the best and most complete data available, and we believe that they fairly and realistically represent the situation as it actually exists in California. The specific considerations entering into each of these estimates are discussed at greater length below.

5.3.1 Injection Timing Errors

Table 5-4 shows the estimated frequency of retarded and advanced fuel injection timing for each class of heavy-duty vehicles. Retarded timing defects include static timing errors (such as would result from misalignment of a fuel injection pump), malfunction of variable timing mechanisms, and problems due to excessive injector lash in DDA and Cummins unit-injector systems. Advanced timing defects include static timing errors (due to tampering or incorrect installation), tampering or malfunction of variable timing mechanisms, and deliberate (or accidental) missetting of injector clearances in DDA engines.

The most significant data on injection timing problems come from the diesel mechanics survey and the EPA/EMA and Cummins studies. In the diesel mechanics survey, the frequency of advanced injection timing ranged from 10-13

TABLE 5-4. ESTIMATED FREQUENCY OF OCCURRENCE OF INJECTION TIMING DEFECTS

Type of Defect	Heavy-Heavy Trucks 1960-1987	Heavy-Heavy Trucks 1988-1990	Heavy-Heavy Trucks 1991-1993	Heavy-Heavy Trucks 1994-Onward	Medium-Heavy Trucks 1960-1987	Medium-Heavy Trucks 1988-1990	Medium-Heavy Trucks 1991-1993	Medium-Heavy Trucks 1994-Onward	Light-Heavy Trucks 1960-1987	Light-Heavy Trucks 1988-1990	Light-Heavy Trucks 1991-1993	Light-Heavy Trucks 1994-Onward	Transit Buses 1960-1987	Transit Buses 1988-1990	Transit Buses 1991-1993	Transit Buses 1994-Onward
INJECTION TIMING																
Injection Timing Advanced																
Cal. Reg./Cal. Eng.	16	20	5	5	15	15	5	5	10	8	5	5	15	3	2	2
Cal. Reg./Fed. Eng.	8	12	5	5	10	12	5	5	10	8	5	5	10	2	2	2
Out of state reg.	8	12	5	5	10	12	5	5	10	8	5	5	—	—	—	—
Injection Timing Retarded																
Cal. Reg./Cal. Eng.	12	10	3	3	6	5	4	4	10	6	4	4	15	5	2	2
Cal. Reg./Fed. Eng.	15	10	3	3	6	5	4	4	10	6	4	4	20	5	2	2
Out of state reg.	15	10	3	3	6	5	4	4	10	6	4	4	—	—	—	—

percent (depending on the category), while the frequency of retarded timing ranged from 5.8 to 7.6 percent. The EPA/EMA data suggest that these estimates are too low, however. In the EPA/EMA study, 5 of 18 heavy-heavy engines showed symptoms of retarded timing, as did four of the 14 engines in the Cummins internal program. Most of the engines with retarded timing in the EPA/EMA study were from Cummins and DDA, one was from Caterpillar. In Cummins and DDA unit-injector systems, injection timing becomes retarded as a result of wear in the injector drivetrain, and must be reset periodically. None of the medium-heavy engines (most of which use in-line pumps) had retarded timing. On the other hand, three medium-heavy (and no heavy-heavy) engines had significantly advanced timing. This may have been due to tampering, but the advantages of tampering with injection timing in a Federal model engine are small.

In developing the estimates in Table 5-4, we assumed that 15 percent of the current-technology (1960-1987) Federal heavy-heavy engines would have retarded timing (mostly due to wear). This represents a compromise between the EPA/EMA data and the mechanics' survey. California's low NO_x standards require substantial timing retardation to begin with, so any additional retardation would be more likely to be noticed and corrected. The incidence of retarded timing is therefore assumed to be smaller in California engines. Medium-heavy engines were assumed to have a much lower incidence of retarded timing, since most of these engines use in-line pumps. Buses use almost entirely DDA unit injector engines, so the incidence of timing problems was estimated to be fairly high. Timing problems in light-heavy engines are due mostly to incorrect installation of the fuel pump, but the distributor-type pumps used in current light-heavy engines are easy to install incorrectly.

The incidence of advanced timing in the medium-heavy class was assumed to be 10 percent for current-technology out-of-state engines, based on the EPA/EMA data showing a 25 percent rate (3 engines out of 12) and the mechanics' survey estimate of 8.6 for "other turbocharged" and 11.7 for naturally aspirated engines. The corresponding rate for out-of-state heavy-

heavy engines was estimated at 8 percent, reflecting the EPA/EMA data (showing no engines with advanced timing), the difficulty of altering the timing on the Cummins engine, and the deleterious effect of this practice on engine life.

In California, where advancing the timing may improve fuel economy and driveability, the incidence of advanced injection timing was estimated to be higher. The mechanics' survey indicated that about 13 percent of "line-haul" engines have advanced timing, but this value is considered somewhat low. This value is expected to increase in future years, due to the continuing low California NO_x standard, and the imposition of a lower Federal NO_x standard in 1990. Not all of this would necessarily reflect tampering; a maintenance error resulting in advanced timing would improve fuel economy and driveability, and is thus unlikely to be referred to a mechanic for correction.

The particulate standards scheduled for 1988, and the stricter NO_x standard scheduled for 1990 will lead to increased use of electronic timing controls on heavy-duty diesels. These controls are expected to be nearly universal beginning in 1991. Injection timing will be under much tighter control with these systems, and thus much less likely to be set improperly. For some systems (those based on electronic unit injectors, for instance), misset timing will be impossible. The advantages of advancing the timing will also be reduced by the more sophisticated control system, while the risks (e.g., of engine damage) will increase. As a result, the incidence of timing problems for post-1991 technology is expected to be quite low.

5.3.2 Fuel Injection Problems

Table 5-5 shows the estimated frequency of occurrence for the three levels of fuel-injection problems defined for this study. These estimates are based primarily on the mechanics' survey and the steady-state results from the visual smoke survey. In the mechanics' survey, 20-22 percent of the trucks in use were estimated to have injectors which were worn or clogged enough to cause excess smoke (corresponding to at least "moderate" injector problems).

TABLE 5-5. ESTIMATED FREQUENCY OF OCCURRENCE OF FUEL INJECTION PROBLEMS

	Heavy-Heavy Trucks				Medium-Heavy Trucks				Light-Heavy Trucks				Transit Buses			
Type of Defect	1960–1987	1988–1990	1991–1993	1994–Onward	1960–1987	1988–1990	1991–1993	1994–Onward	1960–1987	1988–1990	1991–1993	1994–Onward	1960–1987	1988–1990	1991–1993	1994–Onward
FUEL INJECTION PROBLEMS																
Minor Injector Problems																
Cal. Reg./Cal. Eng.	20	18	15	15	20	18	15	15	20	18	15	15	15	10	10	10
Cal. Reg./Fed. Eng.	20	18	15	15	20	18	15	15	20	18	15	15	15	10	10	10
Out of state reg.	20	18	15	15	20	18	15	15	20	18	15	15	—	—	—	—
Moderate Injector Problems																
Cal. Reg./Cal. Eng.	15	13	10	10	15	13	10	10	15	13	10	10	10	7	6	6
Cal. Reg./Fed. Eng.	12	10	8	8	15	13	10	10	15	13	10	10	10	7	6	6
Out of state reg.	8	6	4	4	15	13	10	10	15	13	10	10	—	—	—	—
Severe Injector Problems																
Cal. Reg./Cal. Eng.	4	4	4	4	5	5	5	5	5	5	5	5	2	1	1	1
Cal. Reg./Fed. Eng.	3	3	3	3	5	5	5	5	5	5	5	5	2	1	1	1
Out of state reg.	1	1	1	1	5	5	5	5	5	5	5	5	—	—	—	—

Furthermore, as Figure 5-3 indicates, more than 6 percent of the trucks observed in the visual smoke survey had 20 percent opacity or greater in road-load operation. Most of these trucks were probably suffering from major injector problems. Nearly 20 percent of the trucks fell in the 10 percent opacity range at road load; in most cases, this was probably due to moderate injector problems. Examination of the EPA/EMA data shows that minor injector problems such as worn or leaking injectors occurred in around 15-20 percent of the engines tested. Several moderate and one major injection problem were observed as well.

The values in Table 5-5 were based primarily on these data. The values for heavy-heavy trucks in California were based directly on the smoke survey results. Medium-heavy trucks were assumed to have a similar pattern of injector problems, but a higher rate of moderate and severe problems. Light-heavy trucks were assumed to have similar rates to the medium-heavy trucks. Out-of-state trucks were assumed to have much lower rates of moderate and severe injector problems, since the fuel-economy costs of these problems would be prohibitive in long-haul trucking. The rate of minor injector problems was assumed to be the same, however, since problems at this level have little effect on fuel economy or performance.

5.3.3 Air-Fuel Ratio Problems

Table 5-6 shows the estimated incidence of problems related to air-fuel ratio: misset and disabled smoke limiters, increased maximum fuel rate, dirty air filters, improper or worn-out turbochargers, clogged inter-coolers, and other air-system problems. The considerations entering into these estimates are discussed below.

The estimates of puff-limiter missetting and disablement are based on the mechanics' survey and the acceleration-mode data from the visual smoke survey. As Figure 5-1 shows, the median smoke opacity on acceleration is about 40 percent, and only 35 percent of the trucks have opacities of 20

TABLE 5-6. ESTIMATED FREQUENCY OF OCCURRENCE OF AIR-FUEL RATIO PROBLEMS

Type of Defect	Heavy-Heavy Trucks 1960-1987	1988-1990	1991-1993	1994-Onward	Medium-Heavy Trucks 1960-1987	1988-1990	1991-1993	1994-Onward	Light-Heavy Trucks 1960-1987	1988-1990	1991-1993	1994-Onward	Transit Buses 1960-1987	1988-1990	1991-1993	1994-Onward
AIR-FUEL RATIO PROBLEMS																
Smoke Limiter Misset																
Cal. Reg./Cal. Eng.	29	21	2	0	18	13	2	0	2	5	2	0	5	1	0	0
Cal. Reg./Fed. Eng.	29	21	2	0	18	13	2	0	2	5	2	0	5	1	0	0
Out of state reg.	29	21	2	0	18	13	2	0	2	5	2	0	—	—	—	—
Smoke Limiter Disabled																
Cal. Reg./Cal. Eng.	30	23	5	0	15	12	4	0	1	3	4	0	2	0	0	0
Cal. Reg./Fed. Eng.	30	23	5	0	15	12	4	0	1	3	4	0	2	0	0	0
Out of state reg.	30	23	5	0	15	12	4	0	1	3	4	0	—	—	—	—
Maximum Fuel High																
Cal. Reg./Cal. Eng.	24	18	3	3	14	10	2	2	15	13	5	5	5	1	0	0
Cal. Reg./Fed. Eng.	24	18	3	3	14	10	2	2	15	13	5	5	5	1	0	0
Out of state reg.	24	18	3	3	14	10	2	2	15	13	5	5	—	—	—	—
Clogged Air Filter																
Cal. Reg./Cal. Eng.	22	15	8	8	23	19	10	10	21	19	10	10	15	11	6	6
Cal. Reg./Fed. Eng.	18	14	8	8	23	19	10	10	21	19	10	10	15	11	6	6
Out of state reg.	15	13	8	8	23	19	10	10	21	19	10	10	—	—	—	—
Wrong/Worn Turbo																
Cal. Reg./Cal. Eng.	12	10	5	5	10	9	5	5	5	10	7	7	5	4	4	4
Cal. Reg./Fed. Eng.	11	9	5	5	10	9	5	5	5	10	7	7	5	4	4	4
Out of state reg.	10	9	5	5	10	9	5	5	5	10	7	7	—	—	—	—
Intercooler Clogged																
Cal. Reg./Cal. Eng.	3	7	5	5	1	4	3	3	0	4	3	3	1	4	3	3
Cal. Reg./Fed. Eng.	3	7	5	5	1	4	3	3	0	4	3	3	1	4	3	3
Out of state reg.	3	7	5	5	1	4	3	3	0	4	3	3	—	—	—	—
Other Air-System Problems																
Cal. Reg./Cal. Eng.	15	15	8	8	14	12	8	8	9	12	8	8	10	5	4	4
Cal. Reg./Fed. Eng.	13	15	8	8	14	12	8	8	9	12	8	8	10	5	4	4
Out of state reg.	10	15	8	8	14	12	8	8	9	12	8	8	—	—	—	—

percent or less. In contrast, Table 5-1 shows that nearly all engines manufactured over the last decade have had acceleration average smoke opacities less than or equal to 20 percent on the Federal Certification test, and peak smoke opacities of 35 percent or less. Clearly, engines in use in California emit far more smoke on acceleration than they did when new.

Some of the excess smoke is doubtless due to other types of engine problems, but most of these would also increase smoke in steady-state operation. By comparing the acceleration and full-load smoke opacity data, a reasonable estimate of the frequency of puff-limiter related problems can be obtained. For instance, 16 percent of the trucks observed had acceleration smoke opacities of 60 percent or greater; for comparison, only 4 percent had opacities greater than 30 percent in full-power steady-state operation. Thus, at least 12-16 percent of the trucks observed must have had their puff limiters disabled or seriously maladjusted. By a similar calculation, about 30-40 percent of the trucks must have had their puff limiters misset.

The mechanics' survey indicates that about 29 percent of smoke limiters on line-haul trucks have been reset, and about 30 percent have been disabled. There may have been some confusion on this question, however, since some respondents gave estimates greater than 50 percent for each of these questions, and the two are considered mutually exclusive (that is, a smoke limiter can be reset or disabled, but not both). This may have resulted in an overestimate.

The estimates shown in Table 5-6 reflect these considerations. In addition, we assumed that resetting puff limiters would be most attractive in heavy trucks, and least attractive for light-heavy trucks (many of which are not turbocharged, and which generally have better acceleration performance in any event). It was also assumed that the advent of electronic control systems and traps would make tampering with the puff limiter both more difficult and less rewarding.

The estimated incidence of tampering with the maximum fuel rate shown in the table is based on the mechanic's survey, and is supported by numerous qualitative discussions with knowledgeable parties. There is general agreement that tampering with this parameter is a common occurrence. The smoke survey data were of little help, since nearly all the trucks observed were probably turbocharged, and would not smoke excessively in response to this type of tampering. The lower estimates for the 1988-90, 1991-93, and 1994-2000 time periods reflect our assumption that tamper-resistant electronic governor controls will begin coming into use in 1988, and will be nearly universal by 1991.

The estimated incidence of clogged air filters shown in the table is based on the mechanics' survey. These estimates are also consistent with the data on air filter change frequency from the Survey Data Research report (1981), and with the visual smoke survey. This incidence was projected to go down in future years, as monitoring of boost pressure by the electronic control system would lead to more regular maintenance.

The estimated incidences of worn-out or improper turbochargers, clogged intercoolers, and other air system problems such as pressure leaks, were also based on the mechanics' survey. The incidence of these problems was also projected to decline in future years, as a result of boost pressure monitoring by the electronic control system.

5.3.4 Miscellaneous Engine Problems

Table 5-7 shows our estimates of the frequency of occurrence of "gross emitting" engines--those with high oil consumption, or with mechanical failures that impact emissions. Diesel engines may be "gross emitters" either as a result of excessive wear or of disabling engine problems. Our smoke survey data show a 1-2 percent rate of gross emitters (those with smoke opacity over 20 percent in road load). We have assumed that virtually all of these are California registered (since a truck in such condition is unlikely

TABLE 5-7. ESTIMATED FREQUENCY OF OCCURRENCE OF MISCELLANEOUS PROBLEMS

Type of Defect	Heavy-Heavy Trucks				Medium-Heavy Trucks				Light-Heavy Trucks				Transit Buses			
	1960–1987	1988–1990	1991–1993	1994–Onward	1960–1987	1988–1990	1991–1993	1994–Onward	1960–1987	1988–1990	1991–1993	1994–Onward	1960–1987	1988–1990	1991–1993	1994–Onward
MISCELLANEOUS PROBLEMS																
Engine Mechanical Failure																
Cal. Reg./Cal. Eng.	2	2	2	2	2	2	2	2	2	2	2	2	1	1	1	1
Cal. Reg./Fed. Eng.	1	1	1	1	2	2	2	2	2	2	2	2	1	1	1	1
Out of state reg.	1	1	1	1	1	1	1	1	1	1	1	1	—	—	—	—
High Oil Consumption																
Cal. Reg./Cal. Eng.	5	5	5	5	8	8	8	8	10	10	10	10	5	5	5	5
Cal. Reg./Fed. Eng.	4	4	4	4	8	8	8	8	10	10	10	10	5	5	5	5
Out of state reg.	3	3	3	3	8	8	8	8	10	10	10	10	—	—	—	—

to be driven long-distance). This results in about a 2 percent incidence for California heavy-heavy trucks. We estimate that about half of these visible gross emitters are due to mechanical problems, with the other half due to excessive oil consumption.

Most heavy-heavy engines are overhauled at least once in their lifetimes, generally as a result of high oil consumption or mechanical failure (Survey Data Research, 1983). Due to scheduling problems and the expense of downtime, some time must elapse between the time an overhaul becomes necessary and the time it actually occurs. We assume that this is comparable to the interval between oil changes, or about 12-18,000 miles. The average mileage to overhaul is about 350-500,000 miles for a heavy-heavy vehicle, so that at any given time one would expect that 3-4 percent of the trucks on the road would be in need of an overhaul. Not all of these would show up a gross emitters of visible smoke. Since oil droplets are much less visible than soot particles, excessive oil consumption can increase HC and particulate emissions markedly without greatly increasing smoke opacity.

The rate of gross emitters is assumed to be higher for light-heavy and medium-heavy trucks, since most light-heavy and some medium-heavy engines are not commonly rebuilt. They would thus tend to be used longer after they have worn out or developed significant mechanical problems. Although most gross emitters are older, high-mileage trucks, the incidence of gross emitters is projected to be constant for different model years. As each model-year ages, it will develop excessive wear, high oil consumption, and similar problems.

5.3.5 Future Emission Controls

Table 5-8 shows our estimates of the incidence of problems with future emissions control technologies: electronics failure, tampering with electronic controls (mostly by replacing the PROM), catalyst removal, trap removal/failure, and tampering/failure of the EGR system. The estimated rates

TABLE 5-8. ESTIMATED DEFECT FREQUENCY FOR FUTURE EMISSION CONTROLS

Type of Defect	Heavy-Heavy Trucks 1960–1987	Heavy-Heavy Trucks 1988–1990	Heavy-Heavy Trucks 1991–1993	Heavy-Heavy Trucks 1994–Onward	Medium-Heavy Trucks 1960–1987	Medium-Heavy Trucks 1988–1990	Medium-Heavy Trucks 1991–1993	Medium-Heavy Trucks 1994–Onward	Light-Heavy Trucks 1960–1987	Light-Heavy Trucks 1988–1990	Light-Heavy Trucks 1991–1993	Light-Heavy Trucks 1994–Onward	Transit Buses 1960–1987	Transit Buses 1988–1990	Transit Buses 1991–1993	Transit Buses 1994–Onward
FUTURE EMISSION CONTROLS																
Electronic Control Failure																
Cal. Reg./Cal. Eng.	—	2	5	5	—	2	8	8	—	2	8	8	—	2	2	2
Cal. Reg./Fed. Eng.	—	1	3	3	—	2	8	8	—	2	8	8	—	2	2	2
Out of state reg.	—	1	3	3	—	2	8	8	—	2	8	8	—	—	—	—
Tampering with Electronic Controls																
Cal. Reg./Cal. Eng.	—	5	15	15	—	3	10	10	—	1	7	7	—	2	2	2
Cal. Reg./Fed. Eng.	—	6	20	20	—	3	10	10	—	1	7	7	—	2	2	2
Out of state reg.	—	6	20	20	—	3	10	10	—	1	7	7	—	—	—	—
Catalytic Converter Removed																
Cal. Reg./Cal. Eng.	—	—	6	—	—	—	8	—	—	—	8	—	—	—	—	—
Cal. Reg./Fed. Eng.	—	—	6	—	—	—	8	—	—	—	8	—	—	—	—	—
Out of state reg.	—	—	6	—	—	—	8	—	—	—	8	—	—	—	—	—
Trap-Oxidizer Removed/Disabled																
Cal. Reg./Cal. Eng.	—	—	4	40	—	—	9	30	—	—	15	30	—	—	5	5
Cal. Reg./Fed. Eng.	—	—	5	50	—	—	9	30	—	—	15	30	—	—	5	5
Out of state reg.	—	—	5	50	—	—	9	30	—	—	15	30	—	—	—	—
EGR Disabled																
Cal. Reg./Cal. Eng.	—	—	—	—	—	—	3	6	—	—	6	9	—	—	—	—
Cal. Reg./Fed. Eng.	—	—	—	—	—	—	3	6	—	—	6	9	—	—	—	—
Out of state reg.	—	—	—	—	—	—	3	6	—	—	6	9	—	—	—	—

of electronics failure are based on the assumption that the failure will not be catastrophic. This would include cases where a sensor gave inaccurate,--but not completely out-of-range--values, or where a detected failure left the truck still able to "limp home" using a less sophisticated control strategy. Depending on the degree to which performance is degraded, a truck might spend considerable time in the "limp-home" mode before being repaired.

The estimated frequencies of tampering with electronic controls, traps, and EGR are primarily subjective, based on the observed tendency of truck owners and operators to tamper with engines to improve their performance, fuel economy, etc. These estimates also assume that no effective program (such as an I/M program) is in place to deter such tampering. Replacing a low-emissions PROM with one optimized for performance and fuel economy could generate substantial savings for a truck owner, especially if the truck is used in long-haul service. It would also void the engine warranty, but based on the apparent popularity of tampering with maximum fuel rate controls (which also voids the warranty) this does not appear to be a major concern for many owner/operators. Although such tampering would be technically more difficult than tampering with the maximum fuel rate, the potential rewards would be greater as well. We estimate that future tampering rates for electronic controls will be comparable to, but somewhat less than, the current rates of tampering with the maximum fuel rate.

Removing the catalytic converter would have a similar effect on heavy-duty truck performance as on light-duty trucks--i.e., very little. Since, despite this lack of effect, catalytic converters are removed on 10-50 percent of light-duty trucks (Greco, 1985), it is reasonable to expect some removal from heavy-duty trucks as well. The rates shown assume a 15 percent removal rate for installed catalytic converters, which is comparable to the 14.7 percent rate found by an MVMA study of light-duty vehicles (Survey Data Research, 1985).

Bypassing or removing the particulate trap would also produce some fuel savings and performance improvements, as well as eliminating a device that is likely to be perceived as a safety hazard. Based on the foregoing discussion, we expect tampering with trap-oxidizer systems to be extremely common, especially in long-haul trucks. Bypassing or breaking out a trap would be comparable in difficulty to resetting the smoke limiter on most trucks. As is also the case with the smoke limiter, this should have no effect on the basic engine warranty. Although the only motivation for tampering with the smoke limiter is better acceleration, this tampering is estimated to occur in 40-60 percent of heavy-heavy trucks at present. The motivation for tampering with the trap-oxidizer would be considerably greater. Given these considerations, the estimates shown in Table 5-8 (although very high in absolute terms) can be considered fairly conservative.

EGR systems are known to lead to increased engine wear and oil contamination in diesel engines. They have an especially poor reputation in California, due to bad experience with EGR in California-model Caterpillar 3208 engines. Disabling most EGR systems is easy, and has no ill-effects on the engine other than increased NO_x and possibly noise emissions. As a result, we expect widespread tampering with any EGR systems which may be introduced. This is reflected in the values shown in Table 5-8, which are based on 30 percent tampering with installed EGR systems, and the EGR system installation rate shown in Table 5-3.

6.0 ESTIMATING DEFECT CONSEQUENCES FOR EMISSIONS AND FUEL ECONOMY

In order to assess the impacts of tampering and malmaintenance on air quality, it is clearly essential to develop estimates of the impact of each type of defect on an individual truck's emissions. To evaluate their economic impact, it is also important to estimate their effects on fuel economy. This section presents our estimates of the emissions and fuel-economy impacts of each of the types of defects discussed in Section 3.0, along with the data and other considerations entering into each estimate.

As discussed in Section 4.2, we have chosen to express the emissions and fuel economy impacts of each defect in the form of multiplicative deterioration factors (expressed as a percentage increase or decrease in emissions). Thus, the impact of a specific type of defect is expressed in terms of the percentage increase in emissions from a baseline value, rather than in terms of a number of additional grams per BHP-hr. The increase in g/BHP-hr due to a specific defect can be calculated by multiplying its percentage increase by the appropriate baseline emission factor from Table 4-2. This format was chosen as better representing the nature of the interaction between baseline engine capabilities and emissions increases than an additive approach. In addition, as discussed in Section 4.2, this format makes it easy to model the interaction between different types of defects which may exist on the same vehicle.

Data Sources

Quantitative and qualitative data defining the actual effects of the types of tampering and malmaintenance identified in Section 3.0 are available from a number of sources. In order to develop realistic estimates of emissions effects in everyday use, transient test data--preferably based on the Federal Heavy-Duty Transient Test Procedure--are essential. This is especially true of those defects which most significantly affect emissions during engine transients, such as tampering with puff limiters. For those defects which mostly affect steady-state operation, emissions effects can often be estimated as ratios of steady-state data, and even smoke-opacity data may be relevant. Where they were available and relevant, these data have been used in developing the estimates presented here. Transient cycle data are most directly applicable, however, and reliance has been placed on them wherever possible.

Available transient testing data which are relevant to estimating the emissions impacts of tampering and malmaintenance include the following.

- Data from the EPA/EMA cooperative in-use emissions study (EMA, 1985) discussed in the previous section. These data were extremely valuable, since they included transient and steady-state emissions data for a large number of engines, many of which were suffering from the types of defects discussed here. In addition to the data presented by the EMA, we contacted each manufacturer individually; four of the five participants were able to provide use with additional information on the maintenance status of each of their engines tested (Sienicki, 1986; Schwochert, 1985; Dowdall, 1985; Jorgensen, 1986). These data are given in the Appendix.

- Data from two Cummins internal studies (Jorgensen, 1986; Broering, 1986) provided to us by Cummins. One study--also discussed in the preceding section--was similar to the EMA study discussed above. Another, smaller study examined the effects of different smoke limiter settings on transient emissions. Since both studies included Federal smoke test results and transient emissions, they were especially useful in relating the results of the visual smoke survey to the emissions data.

- Data from Southwest Research Institute (Ullman and Hare, 1985) for two bus engines in which emissions-related defects (timing retard, air-system restrictions, and a disconnected puff-limiter) were deliberately introduced. These data include results from Federal 13-mode, transient, and smoke tests for both the baseline and the malfunctioning condition.

- The New York City Department of Environmental Protection database of diesel emissions tests. This database is discussed at greater length in Volume III. The NYCDEP test program included a large number of test series to examine the effects of specific malfunctions and/or repairs on transient emissions and smoke from transit buses. These tests were made on vehicles, using a chassis dynamometer and one of three driving cycles characteristic of New York City driving. They are thus not directly comparable to Federal Heavy-Duty Transient Test results. They are considered to be equally useful in predicting in-use emissions effects, however.

In addition to these specific studies, we relied on a broad base of data and knowledge from extensive past and ongoing work in the area of emissions control for new heavy-duty diesels, as well as qualitative data and impressions obtained through discussions with manufacturer personnel concerned with engine maintenance and emissions, heavy-duty diesel mechanics, regulatory agency staff, and many other knowledgeable parties.

Limitations--All of the data sources named above have some limitations as to their applicability. Thus, the development of the estimates presented here involved a substantial amount of engineering judgement, and all of them are to some degree subjective. As was also true of the estimated frequencies developed in the preceding section, we have attempted to err on the side of conservatism (that is, of under-estimating emissions effects) in developing these estimates. As a result, we believe that the overall increase in emissions due to tampering and malmaintenance calculated using these estimates may possibly be somewhat less than the true value, but is unlikely to be significantly greater.

6.1 Injection Timing Errors

The emissions effects of injection timing changes are well-defined, since altering injection timing has been one of the major NO_x control techniques used in meeting California's stringent NO_x standards. In direct-injection (DI) engines, retarding injection timing increases particulate emissions and decreases NO_x, while advancing the timing has the reverse effect. Retarding timing also reduces maximum combustion pressure and fuel economy, while advancing the timing increases it. These effects are not linear, however. Figure 6-1, taken from a report by Weaver and coworkers (1984) shows the tradeoff relationship between NO_x and particulate emissions for good current technology (curve A) and for future (roughly 1988-level) advanced technology (curve B). Movement along these curves is accomplished by changing the injection timing--retarding the timing moves the engine operating point to the left in the figure, while advancing it moves it to the right.

At injection timings typical of current Federal engines, small changes in timing usually have only small effects on particulates or fuel economy, but can significantly affect NO_x emissions. At the retarded injection timings characteristic of engines calibrated to California's low NO_x standard, any further retardation can seriously impair combustion--thus dramatically increasing HC and particulate emissions for a relatively small change in NO_x. Advancing the timing from this setting has a lesser, but still quite significant, effect on particulates. These considerations are reflected in the estimates shown in Table 6-1.

Cummins engines using the P-T fuel system are especially sensitive to increased injector lash due to wear. In addition to retarding injection timing, excessive injector lash can prevent the injector plunger from seating at the bottom of its stroke, which markedly increases HC emissions. HC

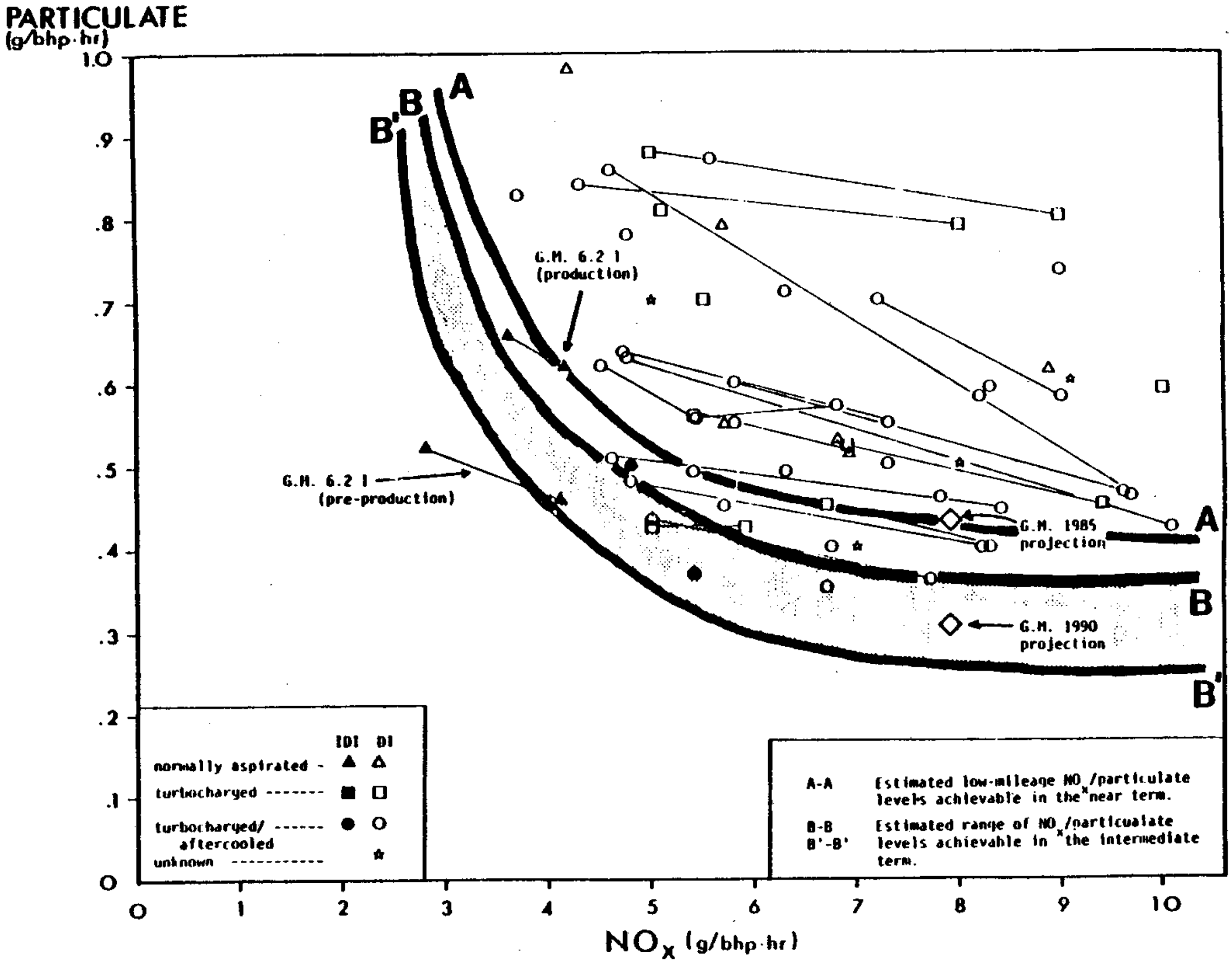


Figure 6-1. NO_x/Particulate Tradeoff Relationship (Weaver et alia, 1984)

TABLE 6-1. ESTIMATED EFFECT OF INJECTION TIMING PROBLEMS ON EMISSIONS AND FUEL CONSUMPTION

	Percent Increase From Baseline															
	1960-1987				1988-1990				1991-1993				1994-Onward			
Type of Defect	NOx	HC	PM	FC	NOx	HC	PM	FC	NOx	HC	PM	FC	NOx	HC	PM	FC
INJECTION TIMING																
Injection Timing Advanced																
Calif. Engine																
Heavy-Heavy	70	0	-25	-7	50	0	-20	-4	60	30	0	-5	60	30	0	-5
Medium-Heavy	70	0	-25	-7	50	0	-20	-4	60	30	0	-5	60	30	0	-5
Light-Heavy	20	-10	10	-7	20	0	10	-4	60	30	0	-5	60	30	0	-5
Transit Bus	70	0	-25	-7	50	0	-20	-4	60	30	0	-5	60	30	0	-5
Federal Engine																
Heavy-Heavy	50	20	10	0	50	20	10	-2	60	30	0	-5	60	30	0	-5
Medium-Heavy	50	20	10	0	50	20	10	-2	60	30	0	-5	60	30	0	-5
Light-Heavy	20	-10	10	0	30	20	10	-2	60	30	0	-5	60	30	0	-5
Transit Bus	50	20	10	0	50	20	10	-2	60	30	0	-5	60	30	0	-5
Injection Timing Retarded																
Calif. Engine																
Heavy-Heavy	-20	50	50	10	-20	50	25	7	-20	50	100	10	-20	50	100	10
Medium-Heavy	-20	30	50	10	-20	20	25	7	-20	50	100	10	-20	50	100	10
Light-Heavy	-20	0	20	5	-20	0	20	5	-20	50	100	10	-20	50	100	10
Transit Bus	-20	30	50	10	-20	20	25	7	-20	50	100	10	-20	50	100	10
Federal Engine																
Heavy-Heavy	-20	50	30	7	-20	50	40	7	-20	50	100	10	-20	50	100	10
Medium-Heavy	-20	-10	30	7	-20	-10	40	7	-20	50	100	10	-20	50	100	10
Light-Heavy	-20	0	20	5	-20	0	20	5	-20	50	100	10	-20	50	100	10
Transit Bus	-20	-10	30	7	-20	-10	40	7	-20	50	100	10	-20	50	100	10

emissions from a Cummins bus engine tested at SWRI increased more than three-fold when the injectors were misset with excessive lash (Ullman and Hare, 1985). Somewhat more than half the heavy-heavy engines in use are Cummins engines using the P-T system. This is reflected in the higher HC impacts for heavy-heavy engines shown in Table 6-1.

Most present light-heavy duty engines are of the indirect-injection (IDI) design, as opposed to the direct injection (DI) system used in all medium-heavy and heavy-heavy engines. Particulate emissions from IDI engines are less sensitive to injection timing than for DI engines, and the relationship between timing and emissions is different. IDI particulate emissions tend to increase when timing is either significantly retarded or significantly advanced from the normal setting. HC emissions from IDI engines are more sensitive to timing than those from DI engines, tending to increase at retarded timing levels. These effects are also reflected in Table 6-1. For future years, it was assumed that the 1988-90 period would see a mix of DI and IDI engines in the light-heavy class, and that DI engines would predominate from 1991 on.

6.2 Fuel Injection Problems

Most fuel injection problems result in poorer mixing between the injected fuel and the charge in the engine cylinder, and thus in higher particulate and HC emissions. This is most commonly due to a reduction in the fuel injection pressure or disruption of the spray pattern by deposits and/or wear. Injection systems using in-line or distributor-type injection pumps may also experience "secondary" injection--injection of a small amount of fuel after the end of the main combustion process--due to weakened hold-down springs. Damaged or badly worn injectors may also leak small amounts of fuel into the combustion chamber. Secondary injection and leakage can greatly increase HC emissions as well as particulates The effects of injection problems on NO_x are usually small, but very serious injection problems may result in some decrease in NO_x due to slower combustion.

Table 6-2 displays our estimates of the emissions effects of the three levels of injection-problem severity defined in Section 3.0. These estimates are based on transient test data developed in the EPA/EMA, SWRI, and NYCDEP studies. The NYCDEP data were especially useful, since they include emissions test data for a number of engines taken both before and after the injectors were removed, cleaned, and recalibrated. These data show that particulate and HC emissions can be significantly degraded even when the smoke test results show little change.

In defining the different levels of severity of injector problems, we defined minor injector problems as those which would show an increase in emissions, but no visible increase in road-load smoke. Moderate injector problems would produce about 10 percent opacity at road load, and severe injector problems would produce 20 percent or more. Since road-load smoke opacity is normally less than 2 percent, the latter two levels represent very significant increases.

The EPA/EMA and NYCDEP studies included a number of engines with minor injector problems. These problems typically increased PM emissions by 20-40 percent. HC increased by 0-20 percent, fuel consumption by 0-4 percent, and NO_x might increase or decrease slightly. Smoke opacity typically increased slightly, but not enough to be noticeable to the eye. These effects were considered representative of those that would be expected from "minor" injection problems.

The NYCDEP database also contains a number of emissions tests in which leaky or bad injectors resulted in road-load smoke opacities of 23-45 percent. Data from these buses are shown in Table 6-3. These cases fit the definition of "severe" injector problems. Comparing the emissions data from these tests to baseline tests without the bad injectors shows that PM emissions were four to ten times higher with the bad injectors, with a net PM increase of about 5-6 g/BHP-hr. HC emissions were increased four to eight times, for an increase of 5-7 g/BHP-hr. NO_x was decreased about 10 percent, while fuel consumption increased about the same amount.

TABLE 6-2. ESTIMATED EFFECT OF FUEL INJECTION PROBLEMS ON EMISSIONS AND FUEL CONSUMPTION

Type of Defect	Percent Increase From Baseline															
	1960-1987				1988-1990				1991-1993				1994-Onward			
	NOx	HC	PM	FC	NOx	HC	PM	FC	NOx	HC	PM	FC	NOx	HC	PM	FC
FUEL INJECTION PROBLEMS																
Minor Injector Problems																
Calif. Engine																
Heavy-Heavy	0	10	35	2	0	10	35	2	0	20	70	2	0	20	70	2
Medium-Heavy	0	10	35	2	0	10	35	2	0	20	70	2	0	20	70	2
Light-Heavy	0	10	20	1	0	10	20	1	0	20	70	2	0	20	70	2
Transit Bus	0	10	35	2	0	10	35	2	0	20	70	2	0	20	70	2
Federal Engine																
Heavy-Heavy	0	10	35	2	0	10	35	2	0	20	70	2	0	20	70	2
Medium-Heavy	0	10	35	2	0	10	35	2	0	20	70	2	0	20	70	2
Light-Heavy	0	10	20	1	0	10	20	1	0	20	70	2	0	20	70	2
Transit Bus	0	10	35	2	0	10	35	2	0	20	70	2	0	20	70	2
Moderate Injector Problems																
Calif. Engine																
Heavy-Heavy	-5	150	200	5	-5	150	200	5	-5	300	400	5	-5	300	400	5
Medium-Heavy	-5	150	200	5	-5	150	200	5	-5	300	400	5	-5	300	400	5
Light-Heavy	-5	150	100	3	-5	150	100	3	-5	300	400	5	-5	300	400	5
Transit Bus	-5	150	200	5	-5	150	200	5	-5	300	400	5	-5	300	400	5
Federal Engine																
Heavy-Heavy	-5	150	200	5	-5	150	200	5	-5	300	400	5	-5	300	400	5
Medium-Heavy	-5	150	200	5	-5	150	200	5	-5	300	400	5	-5	300	400	5
Light-Heavy	-5	150	100	3	-5	150	100	3	-5	300	400	5	-5	300	400	5
Transit Bus	-5	150	200	5	-5	150	200	5	-5	300	400	5	-5	300	400	5

(Continued)

TABLE 6-2. (Continued)

Type of Defect	1960-1987				1988-1990				1991-1993				1994-Onward			
	Percent Increase From Baseline															
	NOx	HC	PM	FC	NOx	HC	PM	FC	NOx	HC	PM	FC	NOx	HC	PM	FC
Severe Injector Problems																
Calif. Engine																
Heavy-Heavy	-10	500	700	10	-10	500	700	10	-10	1100	1500	10	-10	1100	4200	10
Medium-Heavy	-10	500	500	10	-10	500	500	10	-10	1100	1500	10	-10	1100	4200	10
Light-Heavy	-10	500	500	5	-10	500	500	5	-10	1100	1500	10	-10	1100	4200	10
Transit Bus	-10	500	500	10	-10	500	500	10	-10	1100	4200	10	-10	1100	4200	10
Federal Engine																
Heavy-Heavy	-10	500	700	10	-10	500	700	10	-10	1100	1500	10	-10	1100	4200	10
Medium-Heavy	-10	500	500	10	-10	500	500	10	-10	1100	1500	10	-10	1100	4200	10
Light-Heavy	-10	500	500	5	-10	500	500	5	-10	1100	1500	10	-10	1100	4200	10
Transit Bus	-10	500	500	10	-10	500	500	10	-10	1100	4200	10	-10	1100	4200	10

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TABLE 6-3. EFFECT OF SEVERE INJECTOR PROBLEMS ON EMISSIONS: NYCDEP DATA

Smoke Opacity (%)								Emissions: NY Bus 2 Cycle					
Accel. Low	Accel. High	Cruise Low	Cruise High	WOT (D) Low	WOT (D) High	WOT (N) Low	WOT (N) High	HC g/mi	CO g/mi	NOx g/mi	PM g/mi	Fuel MPG	Remarks
BUS 6071 (1971)[1]													
9.0	13.0		0.5	10.0	12.0	5.0	7.0	9.84	96.93	34.64	11.08	3.19	Baseline.
8.0	12.0		0.5	9.0	11.0		2.0	8.31	87.56	35.14	6.70	3.19	After tuneup, new air filter.
64.0	70.0	23.0	27.0	62.0	66.0	26.0	30.0	35.19	175.50	32.23	32.22	2.91	1 leaking injector.
6.0	10.0		0.5	8.0	10.0		2.0	8.15	78.86	38.55	7.43	3.22	1 Plugged injector.
Increase due to leaky injectors								26.88	87.94	-2.91	25.52	-0.28	
Percentage increase								323%	100%	-8%	381%	-9%	
Estimated g/BHP-hr increase								5.23	17.11	-0.57	4.96		
BUS 8074 (1966)													
2.0	3.0		0.5		2.0		2.0	9.43	25.60	46.96	3.76	3.47	Baseline.
1.0	2.0		0.5		1.0	1.0	2.0	8.96	16.19	62.89	3.02	3.45	After tuneup, new air filter.
58.0	62.0	24.0	26.0	58.0	62.0	35.0	41.0	41.00	129.70	61.41	34.43	3.14	1 Leaking injector
2.0	3.0		0.5		1.0	3.0	5.0	9.14	21.26	73.26	4.07	3.45	1 Plugged injector.
Increase due to leaky injectors								32.04	113.51	-1.48	31.41	-0.31	
Percentage increase								358%	701%	-2%	1040%	-9%	
Estimated g/BHP-hr increase								6.23	22.08	-0.29	6.11		
BUS 7525 (1975)													
4.0	6.0		1.0		5.0	2.0	3.0	13.05	16.48	35.03	3.87	3.57	Baseline.
3.0	5.0		0.5		4.0		2.0	7.58	15.55	42.33	2.98	3.89	After tuneup, new air filter.
60.0	65.0	35.0	40.0	60.0	65.0	32.0	36.0	48.03	116.60	37.70	31.94	3.31	1 leaking injector.
4.0	8.0		1.0	5.0	7.0	2.0	4.0	8.33	37.01	44.77	4.16	3.67	1 Plugged injector.
Increase due to leaky injectors								40.45	101.05	-4.63	28.96	-0.58	
Percentage increase								534%	650%	-11%	972%	-15%	
Estimated g/BHP-hr increase								7.87	19.66	-0.90	5.63		

(Continued)

[1] All buses equipped with DDA 6V-71N engines.

TABLE 6-3. (Continued)

Smoke Opacity (%)								Emissions: NY Bus 2 Cycle					
Accel.		Cruise		WOT (D)		WOT (N)		HC	CO	NOx	PM	Fuel	
Low	High	Low	High	Low	High	Low	High	g/mi	g/mi	g/mi	g/mi	MPG	Remarks
BUS 4024 (1969)													
	8.0		0.5		6.0		0.5	7.98	31.07	38.43	4.31	3.83	Original air filter. Baseline.
	11.0		0.5		27.0		44.0	8.37	38.99	36.64	6.93	3.80	Dirty air filter.
85.0	90.0	35.0	40.0		69.0		30.0	45.57	118.00	33.40	28.94	3.50	3 bad injectors, original air filter
	83.0	40.0	45.0		70.0		33.0	43.33	129.20	33.62	29.54	3.40	3 bad injectors and a dirty air filter.
80.0	84.0	35.0	40.0		70.0		33.0	46.20	116.20	35.33		3.50	3 bad injectors and a new air filter.
70.0	77.0	30.0	38.0		70.0	30.0	34.0	45.14	133.80	33.77		3.40	1 bad injector and a dirty air filter.
70.0	75.0	30.0	37.0		70.0	30.0	35.0	46.62	120.50	34.81		3.40	1 bad injector and a new air filter.
70.0	75.0	30.0	35.0		69.0	29.0	35.0	46.79	123.30	34.37	29.44	3.30	1 bad injector, original air filter.
	8.0		0.5		8.0		1.5	11.19	46.97	40.89	3.86	3.80	Original air filter and injectors.
Increase with three bad injectors								37.59	86.93	-5.03	24.63	-0.33	
Percentage increase								471%	280%	-13%	571%	-9%	
Estimated g/BHP-hr increase								7.31	16.91	-0.98	4.79		
BUS 4017 (1969)													
9.0	12.0		0.5		10.0	2.0	7.0	17.20	76.27	39.21	6.15	3.50	Baseline, as received.
8.0	10.0		0.5		8.0	2.0	5.0	17.97	52.70	42.56	4.11	3.70	New air filter.
6.0	9.0		0.5	5.0	7.0		1.5	12.78	42.19	50.26	4.91	3.80	After tune-up, orig. air filter
5.0	7.0		0.5	4.0	5.0	1.0	2.0	14.72	40.47	52.22	7.04	3.70	1 leaking fuel injector, new air filter.
4.0	7.0		1.0	5.0	7.0	2.0	7.0	13.86	52.33	53.11	4.84	3.40	1 leaking, one plugged injector.
60.0	70.0	20.0	24.0	60.0	66.0	24.0	30.0	43.44	147.60	50.74	34.20	3.30	2 leaking, 1 plugged injector.
65.0	73.0	20.0	25.0	64.0	66.0	25.0	30.0	38.26	152.10	47.48	36.70	3.30	2 leaking, 1 plugged injector.
70.0	78.0		16.0	63.0	67.0	21.0	25.0	38.81	121.30	48.87	31.70	3.50	1 badly leaking injector, new air filter.
Increase due to leaky injectors								28.07	107.66	-1.15	30.54	-0.5	Average of two tests with two leaking
Percentage increase								220%	255%	-2%	622%	-13%	injectors vs. " after tuneup"
Estimated g/BHP-hr increase								5.46	20.95	-0.22	5.94		

(Continued)

TABLE 6-3. (Continued)

Smoke Opacity (%)								Emissions: NY Bus 2 Cycle					
Accel.		Cruise		WOT (D)		WOT (N)		HC	CO	NOx	PM	Fuel	
Low	High	Low	High	Low	High	Low	High	g/mi	g/mi	g/mi	g/mi	MPG	Remarks
BUS 7528 (1975)													
2.0	5.0		0.5	2.0	3.0		2.0	7.47	20.52	53.94	7.33	3.40	Baseline.
	2.0		0.5		1.5		1.0	7.31	8.49	57.78	—	3.70	After tune-up.
2.0	4.0		0.5	2.0	3.0		1.0	7.59	25.36	62.10	—	3.30	1 plugged injector, new air filter.
55.0	62.0		21.0	55.0	60.0	16.0	20.0	32.82	118.60	54.19	—	3.40	1 leaking injector, new air cleaner.
Increase due to leaky injectors								25.51	110.11	-3.59	—	-0.3	
Percentage increase								349%	1297%	-6%	—	-8%	
Estimated g/BHP-hr increase								4.96	21.42	-0.70	—		
BUS 8097 (1966)													
	4.0		0.5		4.0		2.0	11.45	37.15	51.99	4.07	3.50	Baseline.
5.0	7.0		0.5		6.0		1.0	11.70	40.81	54.46	4.12	3.48	After tuneup, new air filter.
68.0	72.0	34.0	40.0	68.0	70.0	36.0	38.0	39.75	138.40	49.52	31.04	3.35	1 leaking injector.
5.0	8.0		0.5		5.0		2.0	9.42	48.10	59.49	9.22	3.46	1 plugged injector.
Increase due to leaky injectors								28.05	97.59	-4.94	26.92	-0.13	
Percentage increase								240%	239%	-9%	653%	-4%	
Estimated g/BHP-hr increase								5.46	18.99	-0.96	5.24		

No good examples of "moderate" injector problems were available in our data. In estimating the emissions impact of these problems, we placed them roughly midway between the "minor" and the "severe" injector problems in their effects.

All the buses with severe injector problems in the NYCDEP study were naturally aspirated, and many had rather high PM emissions to begin with. Similar problems in a lower-emitting engine might conceivably result in a lower absolute increase in emissions. In addition, not all "severe" injector problems would necessarily be as severe as these. For conservatism, therefore, we assumed percentage increases in emissions comparable to some of the lower percentages in Table 6-3 for the 1960-87 and 1988-1990 level technologies. For the 1988-1990 technologies, this assumption results in a smaller absolute increase in emissions than for the earlier engines: about 2.7 to 4.4 g/BHP-hr for 1988-1990 engines, compared to about 4.2 to 6.4 g/BHP-hr for pre-1988 engines. Due to their greater use of unit injectors, heavy-heavy engines are probably more susceptible to severe injector problems than are lighter engines. This is also reflected in Table 6-2.

For model years 1991-93, we assumed a similar absolute emissions increase as for 1988-90. Since the baseline emissions are much lower, however, this results in a greater percentage increase. It was also assumed that severe injector problems would quickly destroy a trap-oxidizer, thus resulting in an even larger percentage increase in emissions for 1994 and later vehicles (1991 and later for buses). Light-heavy engines, which are mostly indirect-injected, are less sensitive to fuel injector problems than DI engines; this fact is also reflected in the table.

6.3 Air-Fuel Ratio Problems

Problems with the air-fuel ratio can be divided into two groups: those that affect only transient operation and those which also increase emissions in steady-state running. Tampering with and defeating of puff limiters on turbocharged engines fall into the first category; tampering with the maximum fuel rate, dirty air filters, and other air system problems fall into the second group. The first group is responsible for much of the public offense due to "smoky trucks," but both types of defects are significant from an overall emissions standpoint. Our estimates of the emissions effects of each of these types of defects are given in Table 6-4.

A study by Cummins (Broering, 1986) provides unambiguous data on the effects of tampering with the smoke puff limiter. In the properly adjusted configuration, acceleration peak smoke opacity was 15 percent, well below the Federal standard. Resetting the puff limiter to allow 50 percent peak opacity increased transient cycle particulate emissions by 20 percent. Setting the smoke limiter at the end of its range (in effect, disabling it) gave a peak opacity of 86 percent, and a 50 percent increase in particulates. The estimates in Table 6-4 reflect these data. For future engines (which will have lower baseline emissions) the percentage increases are projected to be greater, but the absolute increase is projected to be less.

Increasing the maximum fuel rate can increase full-power particulate emissions manyfold in naturally-aspirated engines, due to operation at air-fuel ratios beyond the smoke limit. In turbocharged engines, the air supply increases in step with the power output, so the emissions effect is much less --probably some increase in particulate in transient operation, and a small increase in NO_x. Nearly all current light-heavy duty engines are naturally aspirated, as are some medium-heavy and bus engines. Nearly all heavy-heavy duty engines are turbocharged, however. The tighter NO_x and particulate standards scheduled for future years will cause turbochargers to be nearly universal in all classes. The emissions estimates shown in Table 6-4 reflect these facts.

Transient emissions data on the effects of dirty air filters and other air supply problems are very scarce. This is due to the fact that the transient test is conducted on an engine dynamometer, with the air filter and

TABLE 6-4. ESTIMATED EFFECT OF AIR-FUEL RATIO PROBLEMS ON EMISSIONS AND FUEL CONSUMPTION

Type of Defect	Percent Increase From Baseline															
	1960-1987				1988-1990				1991-1993				1994-Onward			
	NOx	HC	PM	FC	NOx	HC	PM	FC	NOx	HC	PM	FC	NOx	HC	PM	FC
AIR-FUEL RATIO PROBLEMS																
Smoke Limiter Misset																
Calif. Engine																
Heavy-Heavy	0	0	20	1	0	0	20	1	0	0	50	1	0	0	50	1
Medium-Heavy	0	0	20	1	0	0	20	1	0	0	50	1	0	0	50	1
Light-Heavy	0	0	20	1	0	0	20	1	0	0	50	1	0	0	50	1
Transit Bus	0	0	20	1	0	0	20	1	0	0	50	1	0	0	50	1
Federal Engine																
Heavy-Heavy	0	0	20	1	0	0	20	1	0	0	50	1	0	0	50	1
Medium-Heavy	0	0	20	1	0	0	20	1	0	0	50	1	0	0	50	1
Light-Heavy	0	0	20	1	0	0	20	1	0	0	50	1	0	0	50	1
Transit Bus	0	0	20	1	0	0	20	1	0	0	50	1	0	0	50	1
Smoke Limiter Disabled																
Calif. Engine																
Heavy-Heavy	0	-20	50	2	0	-20	50	2	0	0	100	2	0	0	100	2
Medium-Heavy	0	-20	50	2	0	-20	50	2	0	0	100	2	0	0	100	2
Light-Heavy	0	-20	50	2	0	-20	50	2	0	0	100	2	0	0	100	2
Transit Bus	0	-20	50	2	0	-20	50	2	0	0	100	2	0	0	100	2
Federal Engine																
Heavy-Heavy	0	-20	50	2	0	-20	50	2	0	0	100	2	0	0	100	2
Medium-Heavy	0	-20	50	2	0	-20	50	2	0	0	100	2	0	0	100	2
Light-Heavy	0	-20	50	2	0	-20	50	2	0	0	100	2	0	0	100	2
Transit Bus	0	-20	50	2	0	-20	50	2	0	0	100	2	0	0	100	2

(Continued)

TABLE 6-4. (Continued)

	Percent Increase From Baseline															
	1960-1987				1988-1990				1991-1993				1994-Onward			
Type of Defect	NOx	HC	PM	FC	NOx	HC	PM	FC	NOx	HC	PM	FC	NOx	HC	PM	FC
Maximum Fuel High																
Calif. Engine																
Heavy-Heavy	10	0	20	2	10	0	30	2	10	0	30	2	10	0	30	2
Medium-Heavy	10	0	30	2	10	0	30	2	10	0	30	2	10	0	30	2
Light-Heavy	10	0	50	2	10	0	50	2	10	0	30	2	10	0	30	2
Transit Bus	10	0	30	2	10	0	30	2	10	0	30	2	10	0	30	2
Federal Engine																
Heavy-Heavy	10	0	20	2	10	0	20	2	10	0	20	2	10	0	20	2
Medium-Heavy	10	0	30	2	10	0	30	2	10	0	30	2	10	0	30	2
Light-Heavy	10	0	50	2	10	0	50	2	10	0	30	2	10	0	30	2
Transit Bus	10	0	30	2	10	0	30	2	10	0	30	2	10	0	30	2
Clogged Air Filter																
Calif. Engine																
Heavy-Heavy	0	0	40	2	0	0	40	2	0	0	50	2	0	0	50	2
Medium-Heavy	0	0	50	2	0	0	50	2	0	0	50	2	0	0	50	2
Light-Heavy	0	0	60	2	0	0	60	2	0	0	50	2	0	0	50	2
Transit Bus	0	0	50	2	0	0	50	2	0	0	50	2	0	0	50	2
Federal Engine																
Heavy-Heavy	0	0	40	2	0	0	40	2	0	0	50	2	0	0	50	2
Medium-Heavy	0	0	50	2	0	0	50	2	0	0	50	2	0	0	50	2
Light-Heavy	0	0	60	2	0	0	60	2	0	0	50	2	0	0	50	2

(Continued)

TABLE 6-4. (Continued)

Type of Defect	Percent Increase From Baseline															
	1960-1987				1988-1990				1991-1993				1994-Onward			
	NOx	HC	PM	FC	NOx	HC	PM	FC	NOx	HC	PM	FC	NOx	HC	PM	FC
Wrong/Worn Turbo																
Calif. Engine																
Heavy-Heavy	0	0	40	1	0	0	40	1	0	0	50	1	0	0	50	1
Medium-Heavy	0	0	40	1	0	0	40	1	0	0	50	1	0	0	50	1
Light-Heavy	0	0	40	1	0	0	40	1	0	0	50	1	0	0	50	1
Transit Bus	-10	0	40	1	-10	0	40	1	0	0	50	1	0	0	50	1
Federal Engine																
Heavy-Heavy	0	0	40	1	0	0	40	1	0	0	50	1	0	0	50	1
Medium-Heavy	0	0	40	1	0	0	40	1	0	0	50	1	0	0	50	1
Light-Heavy	0	0	40	1	0	0	40	1	0	0	50	1	0	0	50	1
Transit Bus	-10	0	40	1	-10	0	40	1	0	0	50	1	0	0	50	1
Intercooler Clogged																
Calif. Engine																
Heavy-Heavy	20	-20	40	2	20	-20	40	2	25	-20	50	2	25	-20	50	2
Medium-Heavy	20	-20	40	2	20	-20	40	2	25	-20	50	2	25	-20	50	2
Light-Heavy	20	-20	40	2	20	-20	40	2	25	-20	50	2	25	-20	50	2
Transit Bus	20	-20	40	2	20	-20	40	2	25	-20	50	2	25	-20	50	2
Federal Engine																
Heavy-Heavy	10	-20	40	2	20	-20	40	2	25	-20	50	2	25	-20	50	2
Medium-Heavy	10	-20	40	2	20	-20	40	2	25	-20	50	2	25	-20	50	2
Light-Heavy	10	-20	40	2	20	-20	40	2	25	-20	50	2	25	-20	50	2
Transit Bus	10	-20	40	2	20	-20	40	2	25	-20	50	2	25	-20	50	2

(Continued)

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TABLE 6-4. (Continued)

Type of Defect	Percent Increase From Baseline															
	1960-1987				1988-1990				1991-1993				1994-Onward			
	NOx	HC	PM	FC	NOx	HC	PM	FC	NOx	HC	PM	FC	NOx	HC	PM	FC
Other Air-System Problems																
Calif. Engine																
Heavy-Heavy	0	0	40	1	0	0	40	1	0	0	40	1	0	0	40	1
Medium-Heavy	0	0	40	1	0	0	40	1	0	0	40	1	0	0	40	1
Light-Heavy	0	0	40	1	0	0	40	1	0	0	40	1	0	0	40	1
Transit Bus	0	0	40	1	0	0	40	1	0	0	40	1	0	0	40	1
Federal Engine																
Heavy-Heavy	0	0	40	1	0	0	40	1	0	0	40	1	0	0	40	1
Medium-Heavy	0	0	40	1	0	0	40	1	0	0	40	1	0	0	40	1
Light-Heavy	0	0	40	1	0	0	40	1	0	0	40	1	0	0	40	1
Transit Bus	0	0	40	1	0	0	40	1	0	0	40	1	0	0	40	1

supply ducting removed and replaced by a preset inlet restriction. Thus, the condition of the air filters, etc. could have no effect on the emissions results from the Cummins and EPA/EMA studies.

The NYCDEP database contains a number of back-to-back tests comparing bus emissions with a dirty air filter to those with a clean one. These typically show a particulate increase of 20-40 percent with the dirty filter, 1-4 percent increase in fuel consumption, and no consistent effect on HC or NO_x emissions. These tests typically show little or no increase in smoke opacity (0-5 percent opacity increase). The diesel mechanics in our survey were asked to estimate the frequency of occurrence of excessive smoke due to air filter clogging, however. The air filters in the NYCDEP tests apparently were not dirty enough to cause excessive smoke. It is likely, therefore that a filter which was dirty enough to cause excessive smoke would also have a greater effect on emissions. For this study, we have assumed that a heavily clogged air filter will increase particulate emissions by 60 percent in naturally-aspirated and two-stroke engines, which are more sensitive to air supply, and by 40 percent in turbocharged engines.

Data on the effects of other air supply problems such as pressure leaks, clogged intercoolers, worn or mismatched turbochargers, etc., are not available. These types of problems would be expected to have similar effects to a clogged air filter, and they were accordingly assigned similar degradation factors for PM and fuel economy. Except for clogged intercoolers, these problems were considered to have little effect on HC or NO_x emissions. A clogged intercooler would increase the charge air temperature, increasing NO_x and decreasing HC emissions.

6.4 Miscellaneous Engine Problems

The miscellaneous engine problems considered in the model are engine mechanical failures (resulting in high emissions) and excessive oil consumption. Engines with these problems tend to be "gross emitters," as indicated by the estimates shown in Table 6-5. For engine mechanical failures, these estimates were based on the emissions results for two engines. One of these was the only clear gross emitter in the EPA/EMA study--a DDA bus engine on which the upper piston rings had collapsed. The other was a Cummins engine with a defective injector cam lobe which was tested as part of the validation testing described in Volume III. The values in Table 6-5 are closer to those for the Cummins than the DDA engine, since the DDA engine also had many other problems could have exaggerated the effect of the mechanical failure.

The effects of excessive oil consumption on diesel emissions were estimated from chassis transient test data published by Braddock and Perry (1986). They tested several light-heavy duty diesel vehicles, including one which was subsequently found to be using excessive oil. Particulate emissions from this truck were double those of a comparable vehicle having the same engine model but with normal oil consumption. HC emissions from the oil-user were five times as great as the normal truck. In this case, the extra oil was apparently showing up mostly in the HC emissions. Some other causes of excess oil use could result in a larger increase in particulates, instead.

6.5 Future Emission Control Technologies

Failure of or tampering with future emissions control technologies can be expected to increase emissions substantially from the controlled level. The most important failure modes will be electronics failures in electronic control systems, tampering with electronic control systems, catalytic converter removal, bypassing or removal of trap-oxidizers, and tampering with exhaust gas recirculation (EGR) systems. The projected emissions effects of each of these occurrences are shown in Table 6-6.

Future electronic control systems will adjust fuel injection timing as a function of engine speed and load in order to minimize HC and particulate emissions at low NO_x levels. Manufacturers have indicated that their electronic control systems will be designed to fail with the timing in a retarded

TABLE 6-5. ESTIMATED EFFECTS OF MISCELLANEOUS ENGINE PROBLEMS ON EMISSIONS AND FUEL CONSUMPTION

	Percent Increase From Baseline															
	1960-1987				1988-1990				1991-1993				1994-Onward			
Type of Defect	NOx	HC	PM	FC	NOx	HC	PM	FC	NOx	HC	PM	FC	NOx	HC	PM	FC
MISCELLANEOUS PROBLEMS																
Engine Mechanical Failure																
Calif. Engine																
Heavy-Heavy	-10	200	150	7	-10	200	150	7	-10	300	300	6	-10	500	500	6
Medium-Heavy	-10	200	150	7	-10	200	150	7	-10	300	300	6	-10	500	500	6
Light-Heavy	-10	200	150	7	-10	200	150	7	-10	300	300	6	-10	500	500	6
Transit Bus	-10	200	150	7	-10	200	150	7	-10	300	300	6	-10	500	500	6
Federal Engine																
Heavy-Heavy	-10	200	150	7	-10	200	150	7	-10	300	300	6	-10	500	500	6
Medium-Heavy	-10	200	150	7	-10	200	150	7	-10	300	300	6	-10	500	500	6
Light-Heavy	-10	200	150	7	-10	200	150	7	-10	300	300	6	-10	500	500	6
Transit Bus	-10	200	150	7	-10	200	150	7	-10	300	300	6	-10	500	500	6
High Oil Consumption																
Calif. Engine																
Heavy-Heavy	0	300	120	0	0	300	150	0	0	300	300	0	0	300	600	0
Medium-Heavy	0	300	120	0	0	300	150	0	0	300	300	0	0	300	600	0
Light-Heavy	0	300	120	0	0	300	150	0	0	300	300	0	0	300	600	0
Transit Bus	0	300	120	0	0	300	150	0	0	300	600	0	0	300	600	0
Federal Engine																
Heavy-Heavy	0	300	150	0	0	300	150	0	0	300	300	0	0	300	600	0
Medium-Heavy	0	300	150	0	0	300	150	0	0	300	300	0	0	300	600	0
Light-Heavy	0	300	150	0	0	300	150	0	0	300	300	0	0	300	600	0
Transit Bus	0	300	150	0	0	300	150	0	0	300	600	0	0	300	600	0

TABLE. 6-6. ESTIMATED EFFECTS OF PROBLEMS WITH FUTURE EMISSION CONTROLS ON EMISSIONS AND FUEL CONSUMPTION

Type of Defect	Percent Increase From Baseline															
	1960-1987				1988-1990				1991-1993				1994-Onward			
	NOx	HC	PM	FC	NOx	HC	PM	FC	NOx	HC	PM	FC	NOx	HC	PM	FC
FUTURE EMISSION CONTROLS																
Electronic Control Failure																
Calif. Engine																
Heavy-Heavy	--	--	--	--	0	30	30	3	0	50	60	3	0	50	60	3
Medium-Heavy	--	--	--	--	0	30	30	4	0	50	60	4	0	50	60	4
Light-Heavy	--	--	--	--	0	30	30	4	0	50	60	4	0	50	60	4
Transit Bus	--	--	--	--	0	30	30	4	0	50	60	4	0	50	60	4
Federal Engine																
Heavy-Heavy	--	--	--	--	0	30	30	3	0	50	60	3	0	50	60	3
Medium-Heavy	--	--	--	--	0	30	30	4	0	50	60	4	0	50	60	4
Light-Heavy	--	--	--	--	0	30	30	4	0	50	60	4	0	50	60	4
Transit Bus	--	--	--	--	0	30	30	4	0	50	60	4	0	50	60	4
Tampering with Electronic Controls																
Calif. Engine																
Heavy-Heavy	--	--	--	--	50	0	0	-5	80	0	50	-5	80	0	50	-5
Medium-Heavy	--	--	--	--	50	0	0	-5	80	0	50	-5	80	0	50	-5
Light-Heavy	--	--	--	--	50	0	0	-5	80	0	50	-5	80	0	50	-5
Transit Bus	--	--	--	--	50	0	0	-5	80	0	50	-5	80	0	50	-5
Federal Engine																
Heavy-Heavy	--	--	--	--	30	0	0	0	80	0	50	-5	80	0	50	-5
Medium-Heavy	--	--	--	--	30	0	0	0	80	0	50	-5	80	0	50	-5
Light-Heavy	--	--	--	--	30	0	0	0	80	0	50	-5	80	0	50	-5
Transit Bus	--	--	--	--	30	0	0	0	80	0	50	-5	80	0	50	-5

(Continued)

TABLE 6-6. (Continued)

Type of Defect	Percent Increase From Baseline															
	1960-1987				1988-1990				1991-1993				1994-Onward			
	NOx	HC	PM	FC	NOx	HC	PM	FC	NOx	HC	PM	FC	NOx	HC	PM	FC
Catalytic Converter Removed																
Calif. Engine																
Heavy-Heavy	--	--	--	--	--	--	--	--	0	100	40	-1	--	--	--	--
Medium-Heavy	--	--	--	--	--	--	--	--	0	100	40	-1	--	--	--	--
Light-Heavy	--	--	--	--	--	--	--	--	0	100	40	-1	--	--	--	--
Transit Bus	--	--	--	--	--	--	--	--	0	100	40	-1	--	--	--	--
Federal Engine																
Heavy-Heavy	--	--	--	--	--	--	--	--	0	100	40	-1	--	--	--	--
Medium-Heavy	--	--	--	--	--	--	--	--	0	100	40	-1	--	--	--	--
Light-Heavy	--	--	--	--	--	--	--	--	0	100	40	-1	--	--	--	--
Transit Bus	--	--	--	--	--	--	--	--	0	100	40	-1	--	--	--	--
EGR Disabled																
Calif. Engine																
Heavy-Heavy	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Medium-Heavy	--	--	--	--	--	--	--	--	35	15	-10	1	35	15	-10	1
Light-Heavy	--	--	--	--	--	--	--	--	50	20	-10	1	50	20	-10	1
Transit Bus	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Federal Engine																
Heavy-Heavy	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Medium-Heavy	--	--	--	--	--	--	--	--	35	15	-10	1	35	15	-10	1
Light-Heavy	--	--	--	--	--	--	--	--	50	20	-10	1	50	20	-10	1
Transit Bus	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--

(Continued)

TABLE 6-6. (Continued)

Type of Defect	Percent Increase From Baseline															
	1960-1987				1988-1990				1991-1993				1994-Onward			
	NOx	HC	PM	FC	NOx	HC	PM	FC	NOx	HC	PM	FC	NOx	HC	PM	FC
Trap-Oxidizer Removed/Disabled																
Calif. Engine																
Heavy-Heavy	--	--	--	--	--	--	--	--	0	40	200	-3	0	100	300	-3
Medium-Heavy	--	--	--	--	--	--	--	--	0	40	200	-4	0	100	300	-4
Light-Heavy	--	--	--	--	--	--	--	--	0	40	200	-4	0	100	300	-4
Transit Bus	--	--	--	--	--	--	--	--	0	40	200	-4	0	100	300	-4
Federal Engine																
Heavy-Heavy	--	--	--	--	--	--	--	--	0	40	200	-3	0	100	300	-3
Medium-Heavy	--	--	--	--	--	--	--	--	0	40	200	-4	0	100	300	-4
Light-Heavy	--	--	--	--	--	--	--	--	0	40	200	-4	0	100	300	-4

position, and with the maximum fueling rate limited to some fraction of the normal full power. The major reason for this is to guard against exceeding the cylinder pressure limits at full load. As a result of this strategy, system failure is likely to have little effect on NO_x, but could significantly increase brake-specific HC and PM emissions.

Tampering with electronic controls will probably take the form of replacing the emissions-optimized engine "map" with one optimized for performance and fuel economy. Such a map would use substantially less retarded timing, and less restrictive control of the transient fueling rate and the maximum steady-state fuel. Advancing timing would increase NO_x emissions to about those of current Federal engines, but would tend to reduce particulates. On the other hand, increasing the fuel rate in transient and full-power operation will increase particulate emissions. At the very low particulate levels characteristic of 1991 and later engines, this is expected to outweigh the reduction due to advancing the timing.

Prototype catalytic converters for diesel use typically reduce PM emissions by 25-35 percent, and HC by 50 percent, or more. Removing the converter would eliminate this effect, resulting in the increases shown.

Removing a particulate trap will naturally increase particulate emissions by a large multiple. For an 80 percent efficient trap, particulate emissions will increase 400 percent if the trap is removed. In addition, even uncatalyzed ceramic monolith traps have some effect in reducing HC emissions, and this effect would be lost if the trap were removed. Naturally, removing a catalytic trap would have an even larger effect on emissions (starting from a smaller baseline) than would the ceramic monolith. We assumed that most traps in model years 1991-93 will be of the non-catalyzed type. For 1994 and later years, we assumed that nearly all traps would incorporate precious-metal catalysts for maximum particulate reduction.

Disabling the exhaust gas recirculation (EGR) system will increase NO_x and HC emissions, but should decrease PM emissions somewhat. Fuel consumption will also increase slightly, since moderate amounts of EGR improve fuel economy.

7.0 EMISSIONS MODEL RESULTS: EMISSION FACTORS

Sections Four, Five, and Six have discussed the model of excess heavy-duty diesel emissions developed by Radian for this project, and have presented the key data and estimates entering into it. This section and the next one present the model results. These results apply to the "base" case--the case in which (as at present) heavy-duty diesel vehicles are not subject to inspection and maintenance requirements. This section presents the results of the emission factor submodel. This submodel calculates the effects of tampering and malmaintenance on vehicle emission factors. Section Eight presents the results of the total emissions model, which converts the emission factors presented in this section into tons per day of emissions.

7.1 Emissions Degradation Factors

The estimated frequency of occurrence of the different tampering and malmaintenance-related defects, and the estimated effects of each type of defect on emissions have been discussed in Sections Five and Six, respectively. In order to calculate the effects of these defects on the overall emission factors, these estimates must first be combined into an overall emissions degradation factor for each class of vehicles, as discussed in Section 4.2.2.

Table 7-1 shows this calculation for one vehicle class: California-registered heavy-heavy trucks with California engines. Similar tables for the other ten classes of heavy-heavy duty vehicles are given in the Appendix. The overall emissions degradation factors calculated in these tables are summarized in Table 7-2.

As Table 7-1 shows, the effect of each type of defect on fleet-average emissions is calculated by multiplying its frequency of occurrence in the fleet by its effect on emissions from vehicles in which it occurs. These calculations indicate that injector problems, tampering with puff limiters,

TABLE 7-1. CALCULATION OF EMISSIONS DEGRADATION FACTORS FOR THE BASELINE CASE

Heavy-Heavy Duty Trucks California Registered California Engines	Frequency of Defect Occurrence Among Trucks in this Class				Oxides of Nitrogen: % Change in Individual Vehicle Emission Factor				Oxides of Nitrogen: % Change in Fleet-Average Emission Factor				Unburned Hydrocarbons: % Change in Individual Vehicle Emission Factor				Unburned Hydrocarbons: % Change in Fleet-Average Emission Factor			
Type of Defect	1980–1987	1988–1990	1991–1993	1994–Onward	1980–1987	1988–1990	1991–1993	1994–Onward	1980–1987	1988–1990	1991–1993	1994–Onward	1980–1987	1988–1990	1991–1993	1994–Onward	1980–1987	1988–1990	1991–1993	1994–Onward
1 Timing Advanced	16%	20%	5%	5%	70%	50%	60%	60%	11.2%	10.0%	3.0%	3.0%	0%	0%	30%	30%	0.0%	0.0%	1.5%	1.5%
2 Timing Retarded	12%	10%	3%	3%	-20%	-20%	-20%	-20%	-2.4%	-2.0%	-0.6%	-0.6%	50%	50%	50%	50%	6.0%	5.0%	1.5%	1.5%
3 Minor Inj. Problems	20%	18%	15%	15%	0%	0%	0%	0%	0.0%	0.0%	0.0%	0.0%	10%	10%	20%	20%	2.0%	1.8%	3.0%	3.0%
4 Mod. Inj. Problems	15%	13%	10%	10%	-5%	-5%	-5%	-5%	-0.8%	-0.7%	-0.5%	-0.5%	150%	150%	300%	300%	22.5%	19.5%	30.0%	30.0%
5 Severe Inj. Problem	4%	4%	4%	4%	-10%	-10%	-10%	-10%	-0.4%	-0.4%	-0.4%	-0.4%	500%	500%	1100%	1100%	20.0%	20.0%	44.0%	44.0%
6 Puff Lt'er Misset	28%	21%	2%	0%	0%	0%	0%	0%	0.0%	0.0%	0.0%	0.0%	0%	0%	0%	0%	0.0%	0.0%	0.0%	0.0%
7 Puff Lt'er Disabled	30%	23%	5%	0%	0%	0%	0%	0%	0.0%	0.0%	0.0%	0.0%	-20%	-20%	0%	0%	-6.0%	-4.6%	0.0%	0.0%
8 Maximum Fuel High	24%	18%	3%	3%	10%	10%	10%	10%	2.4%	1.8%	0.3%	0.3%	0%	0%	0%	0%	0.0%	0.0%	0.0%	0.0%
9 Clogged Air Filter	22%	16%	8%	8%	0%	0%	0%	0%	0.0%	0.0%	0.0%	0.0%	0%	0%	0%	0%	0.0%	0.0%	0.0%	0.0%
10 Wrong/Worn Turbo	12%	10%	5%	5%	0%	0%	0%	0%	0.0%	0.0%	0.0%	0.0%	0%	0%	0%	0%	0.0%	0.0%	0.0%	0.0%
11 Intercooler Clogged	3%	7%	5%	5%	20%	20%	25%	25%	0.6%	1.4%	1.3%	1.3%	-20%	-20%	-20%	-20%	-0.6%	-1.4%	-1.0%	-1.0%
12 Other Air Problems	15%	15%	8%	8%	0%	0%	0%	0%	0.0%	0.0%	0.0%	0.0%	0%	0%	0%	0%	0.0%	0.0%	0.0%	0.0%
13 Engine Mech. Failur	2%	2%	2%	2%	-10%	-10%	-10%	-10%	-0.2%	-0.2%	-0.2%	-0.2%	200%	200%	300%	500%	4.0%	4.0%	6.0%	10.0%
14 Excess Oil Cons.	5%	5%	5%	5%	0%	0%	0%	0%	0.0%	0.0%	0.0%	0.0%	300%	300%	300%	300%	15.0%	15.0%	15.0%	15.0%
15 Electronics Failed	0%	2%	5%	5%	0%	0%	0%	0%	0.0%	0.0%	0.0%	0.0%	0%	30%	50%	50%	0.0%	0.6%	2.5%	2.5%
16 Electronics Tampere	0%	5%	15%	15%	0%	50%	80%	80%	0.0%	2.5%	12.0%	12.0%	0%	0%	0%	0%	0.0%	0.0%	0.0%	0.0%
17 Catalyst Removed	0%	0%	6%	0%	0%	0%	0%	0%	0.0%	0.0%	0.0%	0.0%	0%	0%	100%	0%	0.0%	0.0%	6.0%	0.0%
18 Trap Removed	0%	0%	4%	40%	0%	0%	0%	0%	0.0%	0.0%	0.0%	0.0%	0%	0%	40%	100%	0.0%	0.0%	1.6%	40.0%
19 EGR Disabled	0%	0%	0%	0%	0%	0%	0%	0%	0.0%	0.0%	0.0%	0.0%	0%	0%	0%	0%	0.0%	0.0%	0.0%	0.0%
% Increase Due to All Defects Combined									10.6%	12.7%	15.0%	15.0%					62.3%	59.5%	114.5%	163.5%

TABLE 7-1. (Continued)

Heavy-Heavy Duty Trucks California Registered California Engines	Particulate Matter												Fuel Consumption							
	Frequency of Defect Occurrence Among Trucks in this Class				% Change in Individual Vehicle Emission Factor				% Change in Fleet-Average Emission Factor				% Change in Individual Vehicle Emission Factor				% Change in Fleet-Average Emission Factor			
Type of Defect	1980-1987	1988-1990	1991-1993	1994-Onward	1980-1987	1988-1990	1991-1993	1994-Onward	1980-1987	1988-1990	1991-1993	1994-Onward	1980-1987	1988-1990	1991-1993	1994-Onward	1980-1987	1988-1990	1991-1993	1994-Onward
1 Timing Advanced	16%	20%	5%	5%	-25%	-20%	0%	0%	-4.0%	-4.0%	0.0%	0.0%	-7%	-4%	-5%	-5%	-1.1%	-0.8%	-0.3%	-0.3%
2 Timing Retarded	12%	10%	3%	3%	50%	25%	100%	100%	6.0%	2.5%	3.0%	3.0%	10%	7%	10%	10%	1.2%	0.7%	0.3%	0.3%
3 Minor Inj. Problems	20%	18%	15%	15%	35%	35%	70%	70%	7.0%	6.3%	10.5%	10.5%	2%	2%	2%	2%	0.4%	0.4%	0.3%	0.3%
4 Mod. Inj. Problems	15%	13%	10%	10%	200%	200%	400%	400%	30.0%	26.0%	40.0%	40.0%	5%	5%	5%	5%	0.8%	0.7%	0.5%	0.5%
5 Severe Inj. Problem	4%	4%	4%	4%	700%	700%	1500%	4200%	28.0%	28.0%	60.0%	168.0%	10%	10%	10%	10%	0.4%	0.4%	0.4%	0.4%
6 Puff Lt'er Misset	28%	21%	2%	0%	20%	20%	50%	50%	5.6%	4.2%	1.0%	0.0%	1%	1%	1%	1%	0.3%	0.2%	0.0%	0.0%
7 Puff Lt'er Disabled	30%	23%	5%	0%	50%	50%	100%	100%	15.0%	11.5%	5.0%	0.0%	2%	2%	2%	2%	0.6%	0.5%	0.1%	0.0%
8 Maximum Fuel High	24%	18%	3%	3%	20%	30%	30%	30%	4.8%	5.4%	0.9%	0.9%	2%	2%	2%	2%	0.5%	0.4%	0.1%	0.1%
9 Clogged Air Filter	22%	15%	8%	8%	40%	40%	50%	50%	8.8%	6.0%	4.0%	4.0%	2%	2%	2%	2%	0.4%	0.3%	0.2%	0.2%
10 Wrong/Worn Turbo	12%	10%	5%	5%	40%	40%	50%	50%	4.8%	4.0%	2.5%	2.5%	1%	1%	1%	1%	0.1%	0.1%	0.1%	0.1%
11 Intercooler Clogged	3%	7%	5%	5%	40%	40%	50%	50%	1.2%	2.8%	2.5%	2.5%	2%	2%	2%	2%	0.1%	0.1%	0.1%	0.1%
12 Other Air Problems	15%	15%	8%	8%	40%	40%	40%	40%	6.0%	6.0%	3.2%	3.2%	1%	1%	1%	1%	0.2%	0.2%	0.1%	0.1%
13 Engine Mech. Failur	2%	2%	2%	2%	150%	150%	300%	500%	3.0%	3.0%	6.0%	10.0%	7%	7%	6%	6%	0.1%	0.1%	0.1%	0.1%
14 Excess Oil Cons.	5%	5%	5%	5%	120%	150%	300%	600%	6.0%	7.5%	15.0%	30.0%	0%	0%	0%	0%	0.0%	0.0%	0.0%	0.0%
15 Electronics Failed	0%	2%	5%	5%	0%	30%	60%	60%	0.0%	0.6%	3.0%	3.0%	0%	3%	3%	3%	0.0%	0.1%	0.2%	0.2%
16 Electronics Tampers	0%	5%	15%	15%	0%	0%	50%	50%	0.0%	0.0%	7.5%	7.5%	0%	-6%	-5%	-6%	0.0%	-0.3%	-0.8%	-0.8%
17 Catalyst Removed	0%	0%	6%	0%	0%	0%	40%	0%	0.0%	0.0%	2.4%	0.0%	0%	0%	-1%	0%	0.0%	0.0%	-0.1%	0.0%
18 Trap Removed	0%	0%	4%	40%	0%	0%	200%	300%	0.0%	0.0%	8.0%	120.0%	0%	0%	-3%	-3%	0.0%	0.0%	-0.1%	-1.2%
19 EGR Disabled	0%	0%	0%	0%	0%	0%	0%	0%	0.0%	0.0%	0.0%	0.0%	0%	0%	0%	0%	0.0%	0.0%	0.0%	0.0%
% Increased Due to All Defects Combined									153.4%	130.6%	208.4%	535.6%					4.0%	3.0%	1.2%	0.0%

TABLE 7-2. SUMMARY OF EMISSION DEGRADATION FACTORS CALCULATED IN THE MODEL

			Oxides of Nitrogen				Unburned Hydrocarbons				Particulate Matter				Fuel Consumption			
Vehicle Class	Calif. Reg.	Engine Type	1980-1987	1988-1990	1991-1993	1994-Onward	1980-1987	1988-1990	1991-1993	1994-Onward	1980-1987	1988-1990	1991-1993	1994-Onward	1980-1987	1988-1990	1991-1993	1994-Onward
Heavy	Yes	Calif.	10.6%	12.7%	15.0%	15.0%	62.3%	59.5%	114.5%	163.5%	153.4%	130.6%	208.4%	535.6%	4.0%	3.0%	1.2%	0.0%
	Yes	Federal	2.7%	8.3%	19.4%	19.4%	61.3%	47.3%	89.9%	147.1%	138.6%	118.9%	181.1%	518.9%	4.6%	3.4%	0.6%	-0.9%
	No	Federal	3.1%	8.7%	19.8%	19.8%	32.2%	28.2%	51.6%	103.5%	103.2%	90.7%	123.3%	378.6%	4.0%	3.0%	0.2%	-1.3%
Medium	Yes	Calif.	9.5%	8.6%	11.0%	12.1%	75.7%	72.3%	144.3%	175.3%	131.1%	118.7%	251.5%	535.1%	2.8%	2.6%	1.5%	0.7%
	Yes	Federal	3.9%	8.4%	11.0%	12.1%	75.2%	73.4%	144.3%	175.3%	140.4%	125.5%	251.5%	535.1%	3.7%	3.1%	1.5%	0.7%
	No	Federal	4.0%	8.5%	11.1%	12.2%	73.2%	71.4%	141.3%	170.3%	138.9%	124.0%	248.5%	530.1%	3.7%	3.0%	1.4%	0.6%
Light	Yes	Calif.	0.0%	1.7%	10.9%	12.4%	82.0%	78.3%	154.6%	182.6%	98.2%	104.1%	282.7%	548.1%	1.7%	2.0%	1.5%	0.9%
	Yes	Federal	0.0%	2.3%	10.9%	12.4%	82.0%	81.2%	154.6%	182.6%	101.2%	104.1%	282.7%	548.1%	2.5%	2.2%	1.5%	0.9%
	No	Federal	0.1%	2.4%	11.0%	12.6%	80.0%	79.2%	151.6%	177.6%	99.7%	102.6%	279.7%	543.1%	2.4%	2.2%	1.5%	0.9%
Bus	Yes	Calif.	6.9%	1.4%	2.7%	2.7%	48.0%	34.4%	53.8%	59.5%	71.5%	48.8%	137.7%	147.1%	2.2%	1.4%	0.8%	0.8%
	Yes	Federal	0.3%	0.6%	2.7%	2.7%	42.6%	33.2%	51.4%	53.4%	66.8%	41.8%	118.6%	120.6%	2.6%	1.3%	0.9%	0.9%

dirty air filters and excess oil consumption are the largest contributors to excess HC and particulate emissions at present. Injector problems and oil consumption are projected to remain important in the future. Tampering with trap-oxidizers and other emission controls are also expected to contribute significantly to future excess emissions.

The combined effect of all the individual defect types is calculated by combining their individual effects, using the multiplicative/additive formula diagrammed in Figure 4-2. These values are shown at the bottom of Table 7-1, and again in Table 7-2, along with the combined effects for the other 10 classes. As this table indicates, excess PM and HC emissions are projected to be very significant compared to the baseline emissions, both now and in the future. Excess NO_x emissions, on the other hand, are projected to be relatively small compared to the baseline. Effects on fuel consumption are fairly small in magnitude and mixed in direction, as the beneficial effects of tampering offset the adverse effects of malmaintenance.

7.2 Emission and Fuel Consumption Factors: g/BHP-hr and g/mi

To estimate the increase in emission factors due to tampering and malmaintenance, the emission and fuel consumption factors for each model year shown in Table 4-2 were multiplied by the degradation factors in Table 7-2. The results of this calculation are shown in Table 7-3 for California Registered heavy-heavy duty trucks, and in Appendix A-2 for the other ten classes. Baseline, total, and excess emissions per BHP-hr for each pollutant are shown for each model year. The baseline values shown are the ones given in Table 4-2. The total value is obtained by multiplying the baseline by one plus the degradation factor shown in Table 7-2. Excess emissions (delta) are the difference between the baseline and the total.

The next step in the calculation is to convert the emission factors in g/BHP-hr to g/mile, using the conversion factors listed in Table 4-3. Table 7-4 shows the results of this calculation for California registered

TABLE 7-3. IN-USE EMISSION FACTORS IN G/BHP-HR--CALIFORNIA REGISTERED HEAVY-HEAVY TRUCKS WITH CALIFORNIA ENGINES

Model	Oxides of Nitrogen (g/BHP-hr)				Unburned Hydrocarbons (g/BHP-hr)				Particulate Matter (g/BHP-hr)				Fuel Consumption (lb/BHP-hr)			
Year	Base	Delta	Total	% Incr.	Base	Delta	Total	% Incr.	Base	Delta	Total	% Incr.	Base	Delta	Total	% Incr.
1966	9.00	0.96	9.96	10.6%	0.60	0.37	0.97	62.3%	0.70	1.07	1.77	153.4%	0.43	0.02	0.45	4.0%
1967	9.00	0.96	9.96	10.6%	0.60	0.37	0.97	62.3%	0.70	1.07	1.77	153.4%	0.43	0.02	0.45	4.0%
1968	9.00	0.96	9.96	10.6%	0.60	0.37	0.97	62.3%	0.70	1.07	1.77	153.4%	0.43	0.02	0.45	4.0%
1969	9.00	0.96	9.96	10.6%	0.60	0.37	0.97	62.3%	0.70	1.07	1.77	153.4%	0.43	0.02	0.45	4.0%
1970	9.00	0.96	9.96	10.6%	0.60	0.37	0.97	62.3%	0.70	1.07	1.77	153.4%	0.43	0.02	0.45	4.0%
1971	9.00	0.96	9.96	10.6%	0.60	0.37	0.97	62.3%	0.70	1.07	1.77	153.4%	0.43	0.02	0.45	4.0%
1972	9.00	0.96	9.96	10.6%	0.60	0.37	0.97	62.3%	0.70	1.07	1.77	153.4%	0.43	0.02	0.45	4.0%
1973	9.00	0.96	9.96	10.6%	0.60	0.37	0.97	62.3%	0.70	1.07	1.77	153.4%	0.43	0.02	0.45	4.0%
1974	9.00	0.96	9.96	10.6%	0.60	0.37	0.97	62.3%	0.70	1.07	1.77	153.4%	0.43	0.02	0.45	4.0%
1975	9.00	0.96	9.96	10.6%	0.60	0.37	0.97	62.3%	0.70	1.07	1.77	153.4%	0.43	0.02	0.45	4.0%
1976	9.00	0.96	9.96	10.6%	0.60	0.37	0.97	62.3%	0.70	1.07	1.77	153.4%	0.43	0.02	0.45	4.0%
1977	6.00	0.64	6.64	10.6%	0.60	0.37	0.97	62.3%	0.90	1.38	2.28	153.4%	0.44	0.02	0.46	4.0%
1978	6.00	0.64	6.64	10.6%	0.60	0.37	0.97	62.3%	0.90	1.38	2.28	153.4%	0.43	0.02	0.45	4.0%
1979	6.00	0.64	6.64	10.6%	0.60	0.37	0.97	62.3%	0.90	1.38	2.28	153.4%	0.43	0.02	0.44	4.0%
1980	5.00	0.53	5.53	10.6%	0.60	0.37	0.97	62.3%	0.80	1.23	2.03	153.4%	0.46	0.02	0.47	4.0%
1981	5.00	0.53	5.53	10.6%	0.60	0.37	0.97	62.3%	0.80	1.23	2.03	153.4%	0.44	0.02	0.46	4.0%
1982	5.00	0.53	5.53	10.6%	0.60	0.37	0.97	62.3%	0.80	1.23	2.03	153.4%	0.43	0.02	0.45	4.0%
1983	5.00	0.53	5.53	10.6%	0.60	0.37	0.97	62.3%	0.80	1.23	2.03	153.4%	0.42	0.02	0.44	4.0%
1984	5.00	0.53	5.53	10.6%	0.60	0.37	0.97	62.3%	0.80	1.23	2.03	153.4%	0.41	0.02	0.42	4.0%
1985	5.00	0.53	5.53	10.6%	0.60	0.37	0.97	62.3%	0.80	1.23	2.03	153.4%	0.40	0.02	0.41	4.0%
1986	5.00	0.53	5.53	10.6%	0.60	0.37	0.97	62.3%	0.80	1.23	2.03	153.4%	0.39	0.02	0.40	4.0%
1987	5.00	0.53	5.53	10.6%	0.60	0.37	0.97	62.3%	0.80	1.23	2.03	153.4%	0.37	0.01	0.39	4.0%
1988	5.50	0.70	6.20	12.7%	0.50	0.30	0.80	59.5%	0.55	0.72	1.27	130.6%	0.34	0.01	0.35	3.0%
1989	5.50	0.70	6.20	12.7%	0.50	0.30	0.80	59.5%	0.55	0.72	1.27	130.6%	0.34	0.01	0.35	3.0%
1990	5.50	0.70	6.20	12.7%	0.50	0.30	0.80	59.5%	0.55	0.72	1.27	130.6%	0.34	0.01	0.35	3.0%
1991	4.80	0.72	5.52	15.0%	0.20	0.23	0.43	114.5%	0.22	0.46	0.68	208.4%	0.36	0.00	0.36	1.2%
1992	4.80	0.72	5.52	15.0%	0.20	0.23	0.43	114.5%	0.22	0.46	0.68	208.4%	0.35	0.00	0.36	1.2%
1993	4.80	0.72	5.52	15.0%	0.20	0.23	0.43	114.5%	0.22	0.46	0.68	208.4%	0.35	0.00	0.35	1.2%
1994	4.80	0.72	5.52	15.0%	0.20	0.33	0.53	163.5%	0.08	0.43	0.51	535.6%	0.35	0.00	0.35	0.0%
1995	4.80	0.72	5.52	15.0%	0.20	0.33	0.53	163.5%	0.08	0.43	0.51	535.6%	0.35	0.00	0.35	0.0%
1996	4.80	0.72	5.52	15.0%	0.20	0.33	0.53	163.5%	0.08	0.43	0.51	535.6%	0.34	0.00	0.34	0.0%
1997	4.80	0.72	5.52	15.0%	0.20	0.33	0.53	163.5%	0.08	0.43	0.51	535.6%	0.34	0.00	0.34	0.0%
1998	4.80	0.72	5.52	15.0%	0.20	0.33	0.53	163.5%	0.08	0.43	0.51	535.6%	0.34	0.00	0.34	0.0%
1999	4.80	0.72	5.52	15.0%	0.20	0.33	0.53	163.5%	0.08	0.43	0.51	535.6%	0.34	0.00	0.34	0.0%
2000	4.80	0.72	5.52	15.0%	0.20	0.33	0.53	163.5%	0.08	0.43	0.51	535.6%	0.34	0.00	0.34	0.0%

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TABLE 7-4. IN-USE EMISSION FACTORS IN G/MILE--BY MODEL YEAR--CALIFORNIA REGISTERED HEAVY-HEAVY TRUCKS WITH CALIFORNIA ENGINES

Model	Oxides of Nitrogen (g/mile)				Unburned Hydrocarbons (g/mile)				Particulate Matter (g/mile)				Fuel Consumption (lb/mile)			
Year	Base	Delta	Total	% Incr.	Base	Delta	Total	% Incr.	Base	Delta	Total	% Incr.	Base	Delta	Total	% Incr.
1966	26.25	2.79	29.05	10.6%	1.75	1.09	2.84	62.3%	2.04	3.13	5.17	153.4%	1.25	0.05	1.30	4.0%
1967	26.73	2.84	29.57	10.6%	1.78	1.11	2.89	62.3%	2.08	3.19	5.27	153.4%	1.27	0.05	1.32	4.0%
1968	27.07	2.88	29.95	10.6%	1.80	1.12	2.93	62.3%	2.11	3.23	5.33	153.4%	1.29	0.05	1.34	4.0%
1969	27.41	2.92	30.32	10.6%	1.83	1.14	2.97	62.3%	2.13	3.27	5.40	153.4%	1.31	0.05	1.36	4.0%
1970	27.75	2.95	30.70	10.6%	1.85	1.15	3.00	62.3%	2.16	3.31	5.47	153.4%	1.32	0.05	1.37	4.0%
1971	28.23	3.00	31.23	10.6%	1.88	1.17	3.05	62.3%	2.20	3.37	5.56	153.4%	1.35	0.05	1.40	4.0%
1972	28.71	3.05	31.76	10.6%	1.91	1.19	3.11	62.3%	2.23	3.43	5.66	153.4%	1.37	0.05	1.42	4.0%
1973	28.92	3.08	32.00	10.6%	1.93	1.20	3.13	62.3%	2.25	3.45	5.70	153.4%	1.38	0.05	1.43	4.0%
1974	29.13	3.10	32.23	10.6%	1.94	1.21	3.15	62.3%	2.27	3.48	5.74	153.4%	1.39	0.05	1.44	4.0%
1975	29.34	3.12	32.46	10.6%	1.96	1.22	3.17	62.3%	2.28	3.50	5.78	153.4%	1.40	0.06	1.45	4.0%
1976	29.75	3.16	32.91	10.6%	1.98	1.24	3.22	62.3%	2.31	3.55	5.86	153.4%	1.42	0.06	1.47	4.0%
1977	20.10	2.14	22.24	10.6%	2.01	1.25	3.26	62.3%	3.02	4.62	7.64	153.4%	1.47	0.06	1.53	4.0%
1978	19.78	2.10	21.88	10.6%	1.98	1.23	3.21	62.3%	2.97	4.55	7.52	153.4%	1.42	0.06	1.48	4.0%
1979	19.62	2.09	21.70	10.6%	1.96	1.22	3.18	62.3%	2.94	4.51	7.46	153.4%	1.39	0.06	1.45	4.0%
1980	16.22	1.73	17.94	10.6%	1.95	1.21	3.16	62.3%	2.59	3.98	6.57	153.4%	1.48	0.06	1.54	4.0%
1981	16.08	1.71	17.79	10.6%	1.93	1.20	3.13	62.3%	2.57	3.95	6.52	153.4%	1.43	0.06	1.48	4.0%
1982	15.95	1.70	17.65	10.6%	1.91	1.19	3.11	62.3%	2.55	3.91	6.47	153.4%	1.38	0.05	1.43	4.0%
1983	16.15	1.72	17.86	10.6%	1.94	1.21	3.14	62.3%	2.58	3.96	6.55	153.4%	1.36	0.05	1.41	4.0%
1984	16.34	1.74	18.08	10.6%	1.96	1.22	3.18	62.3%	2.61	4.01	6.62	153.4%	1.34	0.05	1.39	4.0%
1985	16.54	1.76	18.29	10.6%	1.98	1.24	3.22	62.3%	2.65	4.06	6.70	153.4%	1.31	0.05	1.37	4.0%
1986	16.73	1.78	18.51	10.6%	2.01	1.25	3.26	62.3%	2.68	4.11	6.78	153.4%	1.29	0.05	1.34	4.0%
1987	16.93	1.80	18.73	10.6%	2.03	1.27	3.30	62.3%	2.71	4.15	6.86	153.4%	1.27	0.05	1.32	4.0%
1988	18.31	2.33	20.64	12.7%	1.66	0.99	2.65	59.5%	1.83	2.39	4.22	130.6%	1.15	0.03	1.18	3.0%
1989	18.00	2.29	20.29	12.7%	1.64	0.97	2.61	59.5%	1.80	2.35	4.15	130.6%	1.12	0.03	1.15	3.0%
1990	17.70	2.25	19.95	12.7%	1.61	0.96	2.57	59.5%	1.77	2.31	4.08	130.6%	1.08	0.03	1.12	3.0%
1991	15.18	2.28	17.45	15.0%	0.63	0.72	1.36	114.5%	0.70	1.45	2.15	208.4%	1.13	0.01	1.14	1.2%
1992	14.91	2.24	17.14	15.0%	0.62	0.71	1.33	114.5%	0.68	1.42	2.11	208.4%	1.10	0.01	1.11	1.2%
1993	14.85	2.23	17.08	15.0%	0.62	0.71	1.33	114.5%	0.68	1.42	2.10	208.4%	1.08	0.01	1.10	1.2%
1994	14.80	2.22	17.02	15.0%	0.62	1.01	1.62	163.5%	0.25	1.32	1.57	535.6%	1.07	0.00	1.07	0.0%
1995	14.74	2.21	16.95	15.0%	0.61	1.00	1.62	163.5%	0.25	1.32	1.56	535.6%	1.06	0.00	1.06	0.0%
1996	14.69	2.20	16.89	15.0%	0.61	1.00	1.61	163.5%	0.24	1.31	1.56	535.6%	1.05	0.00	1.05	0.0%
1997	14.63	2.19	16.82	15.0%	0.61	1.00	1.61	163.5%	0.24	1.31	1.55	535.6%	1.04	0.00	1.04	0.0%
1998	14.63	2.19	16.82	15.0%	0.61	1.00	1.61	163.5%	0.24	1.31	1.55	535.6%	1.03	0.00	1.03	0.0%
1999	14.63	2.19	16.82	15.0%	0.61	1.00	1.61	163.5%	0.24	1.31	1.55	535.6%	1.03	0.00	1.03	0.0%
2000	14.63	2.19	16.82	15.0%	0.61	1.00	1.61	163.5%	0.24	1.31	1.55	535.6%	1.03	0.00	1.03	0.0%

heavy-heavy trucks. Similar results for the other ten classes are given in Appendix A-3.

7.3 Fleet-Average Emission Factors by Vehicle Class and Calendar Year

The emission factor data presented in Table 7-4 and Appendix A-3 give the estimated average emission factors (in g/mi) for vehicles of a given class and model year. However, the available VMT data are not subdivided by model year: all VMT accumulated by a given class of vehicles in a given year are lumped together. In order to combine the two sets of data, it was necessary to calculate the fleet-average emissions factor for the vehicles of a given class in use in a given calendar year, taking as input the emission factors for each model year and the expected contribution of vehicles of each model year to the total VMT. The procedure for doing this was discussed in Section 4.2.4.

Tables 7-5 through 7-15 show the fleet-average emission and fuel consumption factors calculated in this way for each year from 1985 to 2000, for each class of heavy-duty vehicles considered in the model. The data shown include the baseline emission factors (those which would result if all vehicles were perfectly maintained), the estimated total emission factors (including the effects of tampering and malmaintenance), excess emissions (equal to total minus baseline), and the percent increase in emissions due to malmaintenance and tampering.

As these tables indicate, excess HC and PM emissions due to tampering and malmaintenance are projected to be very significant in all classes of vehicles, while the effects on NO_x emissions and fuel consumption are considerably smaller. Excess fleet-average PM emissions in 1987 are estimated at 0.6 to 4.0 g/mile depending on the vehicle class, or from 67 to 153 percent of baseline emissions. These values are projected to decline somewhat in absolute terms, as new and increasingly more stringent particulate standards come into effect. Excess emissions are not projected to decline as rapidly as

TABLE 7-5. FLEET AVERAGE EMISSION FACTORS IN G/MILE BY CALENDAR YEAR: CALIFORNIA REGISTERED HEAVY-HEAVY TRUCKS WITH CALIFORNIA ENGINES

Cal.	Oxides of Nitrogen (g/mile)				Unburned Hydrocarbons (g/mile)				Particulate Matter (g/mile)				Fuel Consumption (lb/mile)				Fuel Consumption (MPG)			
Year	Base	Delta	Total	% Incr.	Base	Delta	Total	% Incr.	Base	Delta	Total	% Incr.	Base	Delta	Total	% Incr.	Base	Delta	Total	% Incr.
1985	20.14	2.14	22.29	10.6%	1.95	1.21	3.16	62.3%	2.60	3.98	6.58	153.4%	1.38	0.05	1.44	4.0%	5.22	-0.20	5.02	-3.8%
1986	19.30	2.05	21.36	10.6%	1.96	1.22	3.18	62.3%	2.62	4.01	6.63	153.4%	1.37	0.05	1.42	4.0%	5.27	-0.20	5.07	-3.8%
1987	18.72	1.99	20.71	10.6%	1.97	1.23	3.20	62.3%	2.64	4.04	6.68	153.4%	1.35	0.05	1.40	4.0%	5.34	-0.20	5.14	-3.8%
1988	18.49	2.02	20.51	10.9%	1.93	1.20	3.13	62.0%	2.54	3.84	6.37	151.2%	1.32	0.05	1.37	3.8%	5.46	-0.20	5.26	-3.7%
1989	18.32	2.05	20.37	11.2%	1.89	1.16	3.05	61.6%	2.42	3.59	6.01	148.7%	1.29	0.05	1.33	3.7%	5.60	-0.20	5.40	-3.6%
1990	18.15	2.08	20.23	11.4%	1.85	1.13	2.98	61.3%	2.32	3.40	5.72	146.5%	1.25	0.05	1.30	3.6%	5.74	-0.20	5.54	-3.5%
1991	17.70	2.10	19.80	11.9%	1.69	1.08	2.76	63.8%	2.10	3.12	5.22	148.7%	1.23	0.04	1.27	3.3%	5.84	-0.19	5.65	-3.2%
1992	17.23	2.12	19.35	12.3%	1.52	1.02	2.54	67.0%	1.88	2.86	4.74	151.9%	1.21	0.04	1.25	3.0%	5.94	-0.17	5.77	-2.9%
1993	16.86	2.14	19.00	12.7%	1.39	0.97	2.36	70.0%	1.70	2.63	4.33	155.0%	1.19	0.03	1.22	2.8%	6.05	-0.16	5.89	-2.7%
1994	16.54	2.15	18.69	13.0%	1.27	0.97	2.24	76.1%	1.49	2.43	3.91	163.1%	1.17	0.03	1.20	2.4%	6.15	-0.14	6.01	-2.3%
1995	16.04	2.15	18.18	13.4%	1.16	0.96	2.12	83.4%	1.28	2.22	3.50	173.8%	1.15	0.02	1.17	2.0%	6.27	-0.12	6.15	-2.0%
1996	15.79	2.16	17.95	13.6%	1.06	0.96	2.03	90.8%	1.11	2.06	3.17	186.3%	1.13	0.02	1.15	1.7%	6.37	-0.11	6.26	-1.7%
1997	15.60	2.17	17.76	13.9%	0.98	0.96	1.95	98.2%	0.96	1.92	2.88	200.5%	1.11	0.02	1.13	1.4%	6.47	-0.09	6.37	-1.4%
1998	15.43	2.17	17.60	14.1%	0.91	0.96	1.88	105.4%	0.83	1.80	2.63	216.5%	1.10	0.01	1.11	1.2%	6.55	-0.08	6.47	-1.2%
1999	15.29	2.18	17.47	14.3%	0.86	0.96	1.82	112.5%	0.73	1.70	2.43	234.5%	1.09	0.01	1.10	1.0%	6.63	-0.07	6.56	-1.0%
2000	15.18	2.19	17.36	14.4%	0.81	0.97	1.78	119.1%	0.64	1.62	2.26	253.7%	1.08	0.01	1.09	0.8%	6.69	-0.06	6.63	-0.8%

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TABLE 7-6. FLEET AVERAGE EMISSION FACTORS IN G/MILE BY CALENDAR YEAR: CALIFORNIA REGISTERED HEAVY-HEAVY TRUCKS WITH FEDERAL ENGINES

Cal.	Oxides of Nitrogen (g/mile)				Unburned Hydrocarbons (g/mile)				Particulate Matter (g/mile)				Fuel Consumption (lb/mile)				Fuel Consumption (MPG)			
Year	Base	Delta	Total	% Incr.	Base	Delta	Total	% Incr.	Base	Delta	Total	% Incr.	Base	Delta	Total	% Incr.	Base	Delta	Total	% Incr.
1985	26.29	0.71	27.00	2.7%	1.95	1.00	2.94	51.3%	2.27	3.10	5.37	136.6%	1.32	0.06	1.38	4.5%	5.47	-0.24	5.23	-4.3%
1986	25.99	0.70	26.70	2.7%	1.96	1.00	2.96	51.3%	2.28	3.12	5.40	136.6%	1.29	0.06	1.35	4.5%	5.58	-0.24	5.33	-4.3%
1987	25.82	0.70	26.53	2.7%	1.97	1.01	2.98	51.3%	2.30	3.14	5.44	136.6%	1.27	0.06	1.33	4.5%	5.68	-0.25	5.43	-4.3%
1988	25.67	0.88	26.55	3.4%	1.93	0.96	2.89	49.5%	2.20	2.96	5.16	134.7%	1.24	0.05	1.30	4.4%	5.78	-0.24	5.54	-4.2%
1989	25.45	1.07	26.52	4.2%	1.89	0.89	2.78	47.4%	2.08	2.75	4.83	132.4%	1.22	0.05	1.27	4.2%	5.91	-0.24	5.67	-4.1%
1990	24.41	1.14	25.55	4.7%	1.85	0.84	2.69	45.8%	2.02	2.64	4.66	130.2%	1.20	0.05	1.25	4.1%	6.02	-0.24	5.78	-4.0%
1991	23.02	1.38	24.40	6.0%	1.69	0.79	2.48	47.0%	1.85	2.45	4.30	132.2%	1.18	0.04	1.23	3.7%	6.09	-0.22	5.87	-3.5%
1992	21.79	1.62	23.40	7.4%	1.52	0.75	2.27	49.0%	1.67	2.26	3.93	135.4%	1.17	0.04	1.21	3.2%	6.16	-0.19	5.97	-3.1%
1993	20.73	1.81	22.54	8.7%	1.39	0.70	2.09	50.8%	1.52	2.10	3.62	138.3%	1.15	0.03	1.19	2.8%	6.24	-0.17	6.07	-2.7%
1994	19.81	1.97	21.79	10.0%	1.27	0.72	1.99	56.8%	1.34	2.03	3.37	152.1%	1.14	0.03	1.17	2.3%	6.31	-0.14	6.17	-2.3%
1995	18.85	2.14	20.99	11.3%	1.16	0.74	1.90	64.0%	1.15	1.97	3.11	171.1%	1.12	0.02	1.14	1.8%	6.42	-0.11	6.31	-1.7%
1996	18.11	2.26	20.37	12.5%	1.06	0.76	1.82	71.6%	1.00	1.92	2.93	192.3%	1.11	0.02	1.12	1.4%	6.49	-0.09	6.40	-1.3%
1997	17.48	2.37	19.85	13.5%	0.98	0.78	1.76	79.2%	0.87	1.89	2.76	216.3%	1.10	0.01	1.11	1.0%	6.57	-0.06	6.50	-1.0%
1998	16.95	2.45	19.40	14.5%	0.91	0.79	1.71	86.7%	0.77	1.86	2.62	242.8%	1.09	0.01	1.09	0.7%	6.63	-0.04	6.59	-0.7%
1999	16.50	2.53	19.03	15.3%	0.85	0.81	1.66	94.0%	0.67	1.83	2.51	272.2%	1.08	0.00	1.08	0.4%	6.69	-0.03	6.67	-0.4%
2000	16.14	2.59	18.73	16.0%	0.81	0.82	1.63	100.9%	0.60	1.81	2.41	303.4%	1.07	0.00	1.07	0.2%	6.74	-0.01	6.73	-0.2%

TABLE 7-7. FLEET AVERAGE EMISSION FACTORS IN G/MILE BY CALENDAR YEAR: OUT-OF-STATE REGISTERED HEAVY-HEAVY TRUCKS WITH FEDERAL ENGINES

Cal.	Oxides of Nitrogen (g/mile)				Unburned Hydrocarbons (g/mile)				Particulate Matter (g/mile)				Fuel Consumption (lb/mile)				Fuel Consumption (MPG)			
Year	Base	Delta	Total	% Incr.	Base	Delta	Total	% Incr.	Base	Delta	Total	% Incr.	Base	Delta	Total	% Incr.	Base	Delta	Total	% Incr.
1985	26.29	0.82	27.11	3.1%	1.95	0.63	2.57	32.2%	2.27	2.34	4.61	103.2%	1.32	0.05	1.37	4.0%	5.47	-0.21	5.26	-3.9%
1986	25.99	0.81	26.80	3.1%	1.96	0.63	2.59	32.2%	2.28	2.36	4.64	103.2%	1.29	0.05	1.34	4.0%	5.58	-0.21	5.36	-3.9%
1987	25.82	0.81	26.63	3.1%	1.97	0.63	2.61	32.2%	2.30	2.37	4.67	103.2%	1.27	0.05	1.32	4.0%	5.68	-0.22	5.46	-3.9%
1988	25.67	0.98	26.66	3.8%	1.93	0.59	2.53	30.7%	2.20	2.23	4.43	101.5%	1.24	0.05	1.29	3.9%	5.78	-0.22	5.57	-3.7%
1989	25.45	1.17	26.63	4.6%	1.89	0.55	2.43	29.0%	2.08	2.07	4.15	99.4%	1.22	0.05	1.26	3.8%	5.91	-0.21	5.69	-3.6%
1990	24.41	1.24	25.66	5.1%	1.85	0.51	2.36	27.7%	2.02	1.97	4.00	97.4%	1.20	0.04	1.24	3.6%	6.02	-0.21	5.81	-3.5%
1991	23.02	1.48	24.50	6.4%	1.69	0.47	2.16	28.1%	1.85	1.81	3.66	97.8%	1.18	0.04	1.22	3.2%	6.09	-0.19	5.90	-3.1%
1992	21.79	1.71	23.50	7.8%	1.52	0.44	1.96	28.9%	1.67	1.65	3.32	98.8%	1.17	0.03	1.20	2.7%	6.16	-0.16	6.00	-2.7%
1993	20.73	1.90	22.63	9.2%	1.39	0.41	1.80	29.6%	1.52	1.51	3.03	99.7%	1.15	0.03	1.18	2.4%	6.24	-0.14	6.09	-2.3%
1994	19.81	2.06	21.87	10.4%	1.27	0.43	1.70	33.6%	1.34	1.43	2.77	107.0%	1.14	0.02	1.16	1.9%	6.31	-0.12	6.20	-1.8%
1995	18.85	2.22	21.08	11.8%	1.16	0.44	1.60	38.5%	1.15	1.35	2.49	117.2%	1.12	0.02	1.14	1.3%	6.42	-0.09	6.33	-1.3%
1996	18.11	2.34	20.45	12.9%	1.06	0.46	1.53	43.6%	1.00	1.29	2.29	128.6%	1.11	0.01	1.12	0.9%	6.49	-0.06	6.43	-0.9%
1997	17.48	2.45	19.93	14.0%	0.98	0.48	1.46	48.8%	0.87	1.24	2.11	141.7%	1.10	0.01	1.10	0.6%	6.57	-0.04	6.53	-0.6%
1998	16.95	2.53	19.48	14.9%	0.91	0.49	1.41	53.9%	0.77	1.19	1.96	156.0%	1.09	0.00	1.09	0.3%	6.63	-0.02	6.62	-0.3%
1999	16.50	2.61	19.10	15.8%	0.86	0.50	1.36	58.8%	0.67	1.16	1.83	171.9%	1.08	-0.00	1.08	-0.0%	6.69	0.00	6.69	0.0%
2000	16.14	2.66	18.80	16.5%	0.81	0.51	1.33	63.6%	0.60	1.13	1.73	188.9%	1.07	-0.00	1.07	-0.2%	6.74	0.02	6.76	0.2%

TABLE 7-8. FLEET AVERAGE EMISSION FACTORS IN G/MILE BY CALENDAR YEAR: CALIFORNIA REGISTERED MEDIUM-HEAVY TRUCKS WITH CALIFORNIA ENGINES

Cal.	Oxides of Nitrogen (g/mile)				Unburned Hydrocarbons (g/mile)				Particulate Matter (g/mile)				Fuel Consumption (lb/mile)				Fuel Consumption (MPG)			
Year	Base	Delta	Total	% Incr.	Base	Delta	Total	% Incr.	Base	Delta	Total	% Incr.	Base	Delta	Total	% Incr.	Base	Delta	Total	% Incr.
1985	15.53	1.48	17.01	9.5%	1.81	1.37	3.18	75.7%	2.14	2.80	4.94	131.1%	1.31	0.04	1.34	2.8%	5.51	-0.15	5.36	-2.8%
1986	14.61	1.39	16.00	9.5%	1.72	1.30	3.02	75.7%	2.09	2.74	4.82	131.1%	1.27	0.04	1.30	2.8%	5.69	-0.16	5.53	-2.8%
1987	13.78	1.31	15.09	9.5%	1.64	1.24	2.87	75.7%	2.03	2.66	4.68	131.1%	1.22	0.03	1.25	2.8%	5.91	-0.16	5.75	-2.8%
1988	13.27	1.25	14.52	9.4%	1.57	1.14	2.71	72.8%	1.91	2.47	4.38	129.2%	1.16	0.03	1.20	2.8%	6.18	-0.17	6.02	-2.7%
1989	12.86	1.19	14.06	9.3%	1.51	1.04	2.55	69.2%	1.79	2.26	4.05	126.8%	1.11	0.03	1.14	2.8%	6.48	-0.17	6.30	-2.7%
1990	12.60	1.15	13.75	9.1%	1.46	0.95	2.41	65.2%	1.66	2.06	3.72	123.7%	1.06	0.03	1.09	2.7%	6.77	-0.18	6.59	-2.6%
1991	12.19	1.12	13.30	9.2%	1.34	0.91	2.25	67.5%	1.49	1.91	3.40	128.0%	1.03	0.03	1.06	2.5%	6.98	-0.17	6.81	-2.5%
1992	11.81	1.09	12.91	9.3%	1.22	0.88	2.10	71.5%	1.32	1.77	3.09	134.6%	1.00	0.02	1.03	2.3%	7.18	-0.16	7.02	-2.3%
1993	11.47	1.08	12.54	9.4%	1.10	0.85	1.96	77.4%	1.15	1.66	2.81	144.4%	0.98	0.02	1.00	2.1%	7.35	-0.15	7.20	-2.1%
1994	11.23	1.06	12.29	9.4%	1.02	0.86	1.88	84.6%	0.99	1.57	2.56	158.7%	0.96	0.02	0.97	1.9%	7.53	-0.14	7.39	-1.8%
1995	11.04	1.05	12.09	9.5%	0.95	0.88	1.83	92.5%	0.84	1.49	2.34	177.2%	0.94	0.02	0.95	1.6%	7.69	-0.12	7.56	-1.6%
1996	10.87	1.04	11.92	9.6%	0.89	0.90	1.79	101.6%	0.71	1.44	2.14	202.7%	0.92	0.01	0.93	1.4%	7.83	-0.11	7.72	-1.4%
1997	10.74	1.03	11.77	9.6%	0.84	0.92	1.75	109.6%	0.60	1.39	1.99	230.1%	0.90	0.01	0.92	1.2%	7.96	-0.09	7.86	-1.2%
1998	10.64	1.03	11.67	9.7%	0.79	0.93	1.73	117.0%	0.52	1.35	1.86	260.9%	0.89	0.01	0.90	1.0%	8.06	-0.08	7.98	-1.0%
1999	10.56	1.03	11.58	9.7%	0.76	0.94	1.71	123.9%	0.45	1.32	1.76	295.9%	0.88	0.01	0.89	0.9%	8.15	-0.07	8.08	-0.9%
2000	10.49	1.02	11.52	9.8%	0.73	0.96	1.69	130.2%	0.39	1.29	1.68	334.4%	0.88	0.01	0.88	0.8%	8.21	-0.06	8.15	-0.8%

TABLE 7-9. FLEET AVERAGE EMISSION FACTORS IN G/MILE BY CALENDAR YEAR: CALIFORNIA REGISTERED MEDIUM-HEAVY TRUCKS WITH FEDERAL ENGINES

Cal.	Oxides of Nitrogen (g/mile)				Unburned Hydrocarbons (g/mile)				Particulate Matter (g/mile)				Fuel Consumption (lb/mile)				Fuel Consumption (MPG)			
Year	Base	Delta	Total	% Incr.	Base	Delta	Total	% Incr.	Base	Delta	Total	% Incr.	Base	Delta	Total	% Incr.	Base	Delta	Total	% Incr.
1985	21.95	0.85	22.80	3.9%	1.81	1.36	3.17	75.2%	1.87	2.63	4.50	140.4%	1.22	0.05	1.26	3.7%	5.92	-0.21	5.70	-3.6%
1986	21.06	0.81	21.88	3.9%	1.72	1.29	3.01	75.2%	1.83	2.56	4.39	140.4%	1.17	0.04	1.22	3.7%	6.14	-0.22	5.92	-3.6%
1987	20.12	0.78	20.90	3.9%	1.64	1.23	2.87	75.2%	1.77	2.49	4.26	140.4%	1.12	0.04	1.16	3.7%	6.42	-0.23	6.19	-3.6%
1988	19.38	0.80	20.18	4.1%	1.57	1.14	2.71	72.5%	1.66	2.30	3.96	138.7%	1.08	0.04	1.12	3.7%	6.68	-0.24	6.45	-3.5%
1989	18.73	0.83	19.56	4.4%	1.51	1.04	2.55	69.2%	1.54	2.10	3.64	136.4%	1.04	0.04	1.07	3.6%	6.95	-0.24	6.71	-3.4%
1990	17.67	0.84	18.51	4.7%	1.46	0.95	2.42	65.3%	1.45	1.93	3.38	133.2%	1.00	0.03	1.04	3.5%	7.19	-0.24	6.94	-3.4%
1991	16.45	0.86	17.32	5.2%	1.34	0.91	2.25	67.7%	1.31	1.80	3.12	137.7%	0.98	0.03	1.01	3.2%	7.35	-0.23	7.13	-3.1%
1992	15.25	0.88	16.13	5.7%	1.22	0.88	2.10	71.7%	1.17	1.70	2.87	144.5%	0.96	0.03	0.99	2.9%	7.50	-0.21	7.29	-2.8%
1993	14.31	0.91	15.22	6.4%	1.10	0.86	1.96	77.6%	1.03	1.59	2.63	154.6%	0.94	0.02	0.97	2.6%	7.63	-0.19	7.44	-2.5%
1994	13.54	0.93	14.47	6.9%	1.02	0.87	1.89	84.8%	0.89	1.52	2.41	169.9%	0.93	0.02	0.95	2.2%	7.76	-0.17	7.59	-2.2%
1995	12.90	0.95	13.84	7.3%	0.95	0.88	1.83	92.7%	0.77	1.45	2.22	189.8%	0.91	0.02	0.93	1.9%	7.88	-0.15	7.73	-1.9%
1996	12.33	0.96	13.29	7.8%	0.89	0.90	1.79	101.8%	0.65	1.41	2.06	217.0%	0.90	0.01	0.92	1.6%	7.98	-0.13	7.85	-1.6%
1997	11.87	0.97	12.84	8.2%	0.84	0.92	1.75	109.8%	0.55	1.36	1.92	245.6%	0.89	0.01	0.90	1.4%	8.08	-0.11	7.97	-1.3%
1998	11.50	0.98	12.48	8.5%	0.79	0.93	1.73	117.2%	0.48	1.33	1.81	277.4%	0.88	0.01	0.89	1.2%	8.15	-0.09	8.06	-1.1%
1999	11.20	0.99	12.19	8.8%	0.76	0.95	1.71	124.1%	0.42	1.30	1.72	312.8%	0.88	0.01	0.89	1.0%	8.21	-0.08	8.13	-1.0%
2000	10.97	1.00	11.97	9.1%	0.73	0.96	1.69	130.4%	0.37	1.29	1.65	351.3%	0.87	0.01	0.88	0.8%	8.26	-0.07	8.19	-0.8%

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TABLE 7-10. FLEET AVERAGE EMISSION FACTORS IN G/MILE BY CALENDAR YEAR: OUT-OF-STATE REGISTERED MEDIUM-HEAVY TRUCKS WITH FEDERAL ENGINES

Cal.	Oxides of Nitrogen (g/mile)				Unburned Hydrocarbons (g/mile)				Particulate Matter (g/mile)				Fuel Consumption (lb/mile)				Fuel Consumption (MPG)			
Year	Base	Delta	Total	% Incr.	Base	Delta	Total	% Incr.	Base	Delta	Total	% Incr.	Base	Delta	Total	% Incr.	Base	Delta	Total	% Incr.
1985	21.95	0.87	22.82	4.0%	1.81	1.32	3.13	73.2%	1.87	2.60	4.48	138.9%	1.22	0.04	1.26	3.7%	5.92	-0.21	5.71	-3.5%
1986	21.06	0.84	21.90	4.0%	1.72	1.26	2.98	73.2%	1.83	2.54	4.36	138.9%	1.17	0.04	1.21	3.7%	6.14	-0.22	5.93	-3.5%
1987	20.12	0.80	20.92	4.0%	1.64	1.20	2.83	73.2%	1.77	2.46	4.23	138.9%	1.12	0.04	1.16	3.7%	6.42	-0.23	6.19	-3.5%
1988	19.38	0.82	20.20	4.2%	1.57	1.11	2.68	70.5%	1.66	2.27	3.93	137.2%	1.08	0.04	1.12	3.6%	6.68	-0.23	6.45	-3.5%
1989	18.73	0.85	19.58	4.5%	1.51	1.01	2.52	67.2%	1.54	2.08	3.62	134.9%	1.04	0.04	1.07	3.5%	6.95	-0.24	6.71	-3.4%
1990	17.67	0.86	18.53	4.8%	1.46	0.93	2.39	63.3%	1.45	1.91	3.36	131.7%	1.00	0.03	1.04	3.4%	7.19	-0.24	6.95	-3.3%
1991	16.46	0.88	17.33	5.3%	1.34	0.88	2.23	65.7%	1.31	1.78	3.09	136.2%	0.98	0.03	1.01	3.1%	7.35	-0.22	7.13	-3.0%
1992	15.25	0.89	16.14	5.8%	1.22	0.86	2.08	69.6%	1.17	1.68	2.85	142.9%	0.96	0.03	0.99	2.8%	7.50	-0.21	7.30	-2.7%
1993	14.31	0.92	15.23	6.5%	1.10	0.83	1.94	75.4%	1.03	1.58	2.61	152.8%	0.94	0.02	0.97	2.5%	7.63	-0.19	7.44	-2.4%
1994	13.54	0.94	14.49	7.0%	1.02	0.84	1.86	82.3%	0.89	1.50	2.39	168.0%	0.93	0.02	0.95	2.2%	7.76	-0.16	7.59	-2.1%
1995	12.90	0.96	13.86	7.4%	0.95	0.85	1.80	90.0%	0.77	1.44	2.21	187.8%	0.91	0.02	0.93	1.8%	7.88	-0.14	7.73	-1.8%
1996	12.33	0.97	13.31	7.9%	0.89	0.88	1.76	98.8%	0.65	1.39	2.04	214.9%	0.90	0.01	0.92	1.5%	7.98	-0.12	7.86	-1.5%
1997	11.87	0.98	12.85	8.3%	0.84	0.89	1.73	106.5%	0.56	1.35	1.90	243.3%	0.89	0.01	0.90	1.3%	8.08	-0.10	7.97	-1.3%
1998	11.50	0.99	12.49	8.6%	0.79	0.90	1.70	113.7%	0.48	1.32	1.80	274.8%	0.88	0.01	0.89	1.1%	8.15	-0.09	8.06	-1.1%
1999	11.20	1.00	12.21	8.9%	0.76	0.92	1.68	120.3%	0.42	1.29	1.71	310.1%	0.88	0.01	0.88	0.9%	8.21	-0.08	8.14	-0.9%
2000	10.97	1.01	11.98	9.2%	0.73	0.93	1.66	126.4%	0.37	1.28	1.64	348.3%	0.87	0.01	0.88	0.8%	8.26	-0.06	8.20	-0.8%

TABLE 7-11. FLEET AVERAGE EMISSION FACTORS IN G/MILE BY CALENDAR YEAR: CALIFORNIA REGISTERED LIGHT-HEAVY TRUCKS WITH CALIFORNIA ENGINES

Cal.	Oxides of Nitrogen (g/mile)				Unburned Hydrocarbons (g/mile)				Particulate Matter (g/mile)				Fuel Consumption (lb/mile)				Fuel Consumption (MPG)			
Year	Base	Delta	Total	% Incr.	Base	Delta	Total	% Incr.	Base	Delta	Total	% Incr.	Base	Delta	Total	% Incr.	Base	Delta	Total	% Incr.
1985	4.39	0.00	4.39	0.0%	0.68	0.56	1.24	82.0%	0.59	0.58	1.16	98.2%	0.51	0.01	0.52	1.7%	14.12	-0.24	13.88	-1.7%
1986	4.38	0.00	4.38	0.0%	0.68	0.56	1.23	82.0%	0.58	0.57	1.16	98.2%	0.51	0.01	0.52	1.7%	14.15	-0.24	13.90	-1.7%
1987	4.37	0.00	4.37	0.0%	0.68	0.56	1.23	82.0%	0.58	0.57	1.15	98.2%	0.51	0.01	0.52	1.7%	14.17	-0.24	13.93	-1.7%
1988	4.52	0.02	4.53	0.4%	0.66	0.51	1.17	77.1%	0.57	0.56	1.13	97.3%	0.50	0.01	0.51	1.8%	14.26	-0.25	14.01	-1.7%
1989	4.66	0.03	4.69	0.6%	0.64	0.46	1.11	72.1%	0.56	0.54	1.11	96.4%	0.50	0.01	0.51	1.8%	14.42	-0.26	14.16	-1.8%
1990	4.76	0.04	4.80	0.8%	0.63	0.43	1.06	68.3%	0.56	0.53	1.09	95.7%	0.49	0.01	0.50	1.8%	14.62	-0.26	14.35	-1.8%
1991	4.75	0.08	4.83	1.8%	0.58	0.42	1.00	71.6%	0.51	0.54	1.05	106.6%	0.49	0.01	0.49	1.7%	14.82	-0.25	14.56	-1.7%
1992	4.71	0.13	4.84	2.8%	0.53	0.41	0.94	76.5%	0.46	0.55	1.01	120.3%	0.48	0.01	0.49	1.7%	15.04	-0.24	14.79	-1.6%
1993	4.69	0.16	4.85	3.5%	0.49	0.40	0.89	80.7%	0.42	0.56	0.98	133.1%	0.47	0.01	0.48	1.6%	15.24	-0.24	15.01	-1.6%
1994	4.66	0.19	4.86	4.2%	0.46	0.40	0.86	87.3%	0.37	0.56	0.93	150.6%	0.47	0.01	0.47	1.5%	15.43	-0.22	15.21	-1.4%
1995	4.64	0.22	4.86	4.7%	0.43	0.41	0.84	94.3%	0.33	0.56	0.88	170.9%	0.46	0.01	0.47	1.3%	15.61	-0.20	15.40	-1.3%
1996	4.61	0.24	4.85	5.2%	0.41	0.41	0.82	100.9%	0.29	0.55	0.84	192.6%	0.46	0.01	0.46	1.2%	15.77	-0.19	15.58	-1.2%
1997	4.59	0.26	4.85	5.6%	0.39	0.41	0.80	107.4%	0.25	0.55	0.81	217.0%	0.45	0.01	0.46	1.1%	15.92	-0.18	15.74	-1.1%
1998	4.57	0.27	4.84	6.0%	0.37	0.42	0.79	113.3%	0.23	0.55	0.78	242.3%	0.45	0.00	0.45	1.0%	16.05	-0.16	15.89	-1.0%
1999	4.55	0.28	4.84	6.3%	0.35	0.42	0.77	118.8%	0.20	0.55	0.76	269.6%	0.45	0.00	0.45	1.0%	16.17	-0.15	16.01	-0.9%
2000	4.54	0.30	4.83	6.5%	0.34	0.42	0.76	124.0%	0.18	0.55	0.73	298.2%	0.44	0.00	0.45	0.9%	16.27	-0.14	16.12	-0.9%

TABLE 7-12. FLEET AVERAGE EMISSION FACTORS IN G/MILE BY CALENDAR YEAR: CALIFORNIA REGISTERED LIGHT-HEAVY TRUCKS WITH FEDERAL ENGINES

Cal.	Oxides of Nitrogen (g/mile)				Unburned Hydrocarbons (g/mile)				Particulate Matter (g/mile)				Fuel Consumption (lb/mile)				Fuel Consumption (MPG)			
Year	Base	Delta	Total	% Incr.	Base	Delta	Total	% Incr.	Base	Delta	Total	% Incr.	Base	Delta	Total	% Incr.	Base	Delta	Total	% Incr.
1985	4.39	0.00	4.39	0.0%	0.68	0.56	1.24	82.0%	0.59	0.59	1.18	101.2%	0.51	0.01	0.52	2.5%	14.12	-0.34	13.78	-2.4%
1986	4.38	0.00	4.38	0.0%	0.68	0.56	1.23	82.0%	0.58	0.59	1.17	101.2%	0.51	0.01	0.52	2.5%	14.15	-0.34	13.81	-2.4%
1987	4.37	0.00	4.37	0.0%	0.68	0.56	1.23	82.0%	0.58	0.59	1.17	101.2%	0.51	0.01	0.52	2.5%	14.17	-0.34	13.83	-2.4%
1988	4.52	0.02	4.54	0.5%	0.66	0.51	1.17	77.4%	0.57	0.57	1.14	99.8%	0.50	0.01	0.52	2.4%	14.26	-0.34	13.93	-2.4%
1989	4.66	0.04	4.70	0.9%	0.64	0.47	1.11	72.7%	0.56	0.55	1.12	98.4%	0.50	0.01	0.51	2.4%	14.42	-0.33	14.09	-2.3%
1990	4.76	0.05	4.81	1.1%	0.63	0.44	1.07	69.2%	0.56	0.54	1.10	97.4%	0.49	0.01	0.50	2.3%	14.62	-0.33	14.29	-2.3%
1991	4.75	0.10	4.84	2.1%	0.58	0.42	1.00	72.6%	0.51	0.55	1.06	108.1%	0.49	0.01	0.50	2.2%	14.82	-0.32	14.51	-2.1%
1992	4.71	0.14	4.85	3.0%	0.53	0.41	0.94	77.3%	0.46	0.56	1.02	121.8%	0.48	0.01	0.49	2.0%	15.04	-0.30	14.74	-2.0%
1993	4.69	0.17	4.86	3.7%	0.49	0.40	0.89	81.4%	0.42	0.56	0.98	134.4%	0.47	0.01	0.48	1.9%	15.25	-0.28	14.97	-1.9%
1994	4.66	0.20	4.86	4.3%	0.46	0.40	0.86	88.0%	0.37	0.56	0.93	151.6%	0.47	0.01	0.47	1.7%	15.44	-0.26	15.18	-1.7%
1995	4.64	0.23	4.86	4.9%	0.43	0.41	0.84	95.0%	0.33	0.56	0.89	172.0%	0.46	0.01	0.47	1.5%	15.61	-0.24	15.37	-1.5%
1996	4.61	0.25	4.86	5.3%	0.41	0.41	0.82	101.5%	0.29	0.56	0.85	193.7%	0.46	0.01	0.46	1.4%	15.77	-0.22	15.55	-1.4%
1997	4.59	0.26	4.85	5.7%	0.39	0.42	0.80	107.9%	0.25	0.56	0.81	218.0%	0.45	0.01	0.46	1.3%	15.92	-0.20	15.72	-1.2%
1998	4.57	0.28	4.85	6.1%	0.37	0.42	0.79	113.8%	0.23	0.55	0.78	243.2%	0.45	0.01	0.45	1.2%	16.05	-0.18	15.87	-1.1%
1999	4.55	0.29	4.84	6.3%	0.35	0.42	0.77	119.3%	0.20	0.55	0.76	270.4%	0.45	0.00	0.45	1.1%	16.17	-0.17	16.00	-1.1%
2000	4.54	0.30	4.83	6.6%	0.34	0.42	0.76	124.4%	0.18	0.55	0.74	298.9%	0.44	0.00	0.46	1.0%	16.27	-0.16	16.11	-1.0%

TABLE 7-13. FLEET AVERAGE EMISSION FACTORS IN G/MILE BY CALENDAR YEAR: OUT-OF-STATE REGISTERED LIGHT-HEAVY TRUCKS WITH FEDERAL ENGINES

Cal.	Oxides of Nitrogen (g/mile)				Unburned Hydrocarbons (g/mile)				Particulate Matter (g/mile)				Fuel Consumption (lb/mile)				Fuel Consumption (MPG)			
Year	Base	Delta	Total	% Incr.	Base	Delta	Total	% Incr.	Base	Delta	Total	% Incr.	Base	Delta	Total	% Incr.	Base	Delta	Total	% Incr.
1985	4.39	0.01	4.40	0.1%	0.68	0.54	1.22	80.0%	0.59	0.58	1.17	99.7%	0.51	0.01	0.52	2.4%	14.12	-0.33	13.79	-2.3%
1986	4.38	0.01	4.38	0.1%	0.68	0.54	1.22	80.0%	0.58	0.58	1.17	99.7%	0.51	0.01	0.52	2.4%	14.15	-0.33	13.82	-2.3%
1987	4.37	0.01	4.37	0.1%	0.68	0.54	1.22	80.0%	0.58	0.58	1.16	99.7%	0.51	0.01	0.52	2.4%	14.17	-0.33	13.84	-2.3%
1988	4.52	0.03	4.54	0.6%	0.66	0.50	1.16	75.4%	0.57	0.56	1.14	98.3%	0.50	0.01	0.52	2.3%	14.26	-0.33	13.94	-2.3%
1989	4.66	0.04	4.71	1.0%	0.64	0.46	1.10	70.7%	0.56	0.55	1.11	96.9%	0.50	0.01	0.51	2.3%	14.42	-0.32	14.10	-2.2%
1990	4.76	0.06	4.82	1.2%	0.63	0.42	1.05	67.2%	0.56	0.53	1.09	95.9%	0.49	0.01	0.50	2.3%	14.62	-0.32	14.30	-2.2%
1991	4.75	0.10	4.85	2.2%	0.58	0.41	0.99	70.5%	0.51	0.54	1.05	106.6%	0.49	0.01	0.50	2.1%	14.82	-0.31	14.52	-2.1%
1992	4.71	0.15	4.86	3.1%	0.53	0.40	0.93	75.2%	0.46	0.55	1.01	120.1%	0.48	0.01	0.49	1.9%	15.04	-0.29	14.75	-1.9%
1993	4.69	0.18	4.86	3.8%	0.49	0.39	0.88	79.2%	0.42	0.56	0.97	132.6%	0.47	0.01	0.48	1.8%	15.25	-0.27	14.98	-1.8%
1994	4.66	0.21	4.87	4.4%	0.46	0.39	0.85	85.6%	0.37	0.56	0.93	149.9%	0.47	0.01	0.47	1.6%	15.44	-0.25	15.19	-1.6%
1995	4.64	0.23	4.87	5.0%	0.43	0.40	0.83	92.3%	0.33	0.55	0.88	170.0%	0.46	0.01	0.47	1.5%	15.61	-0.23	15.38	-1.5%
1996	4.61	0.25	4.86	5.4%	0.41	0.40	0.81	98.6%	0.29	0.55	0.84	191.6%	0.46	0.01	0.46	1.3%	15.77	-0.21	15.56	-1.3%
1997	4.59	0.27	4.86	5.8%	0.39	0.40	0.79	104.8%	0.25	0.55	0.80	215.7%	0.45	0.01	0.46	1.2%	15.92	-0.19	15.73	-1.2%
1998	4.57	0.28	4.85	6.2%	0.37	0.41	0.78	110.4%	0.23	0.55	0.78	240.8%	0.45	0.00	0.45	1.1%	16.05	-0.17	15.88	-1.1%
1999	4.55	0.29	4.84	6.4%	0.35	0.41	0.76	115.8%	0.20	0.56	0.75	267.9%	0.45	0.00	0.45	1.0%	16.17	-0.16	16.01	-1.0%
2000	4.54	0.30	4.84	6.7%	0.34	0.41	0.75	120.7%	0.18	0.56	0.73	296.2%	0.44	0.00	0.45	0.9%	16.27	-0.15	16.12	-0.9%

TABLE 7-14. FLEET AVERAGE EMISSION FACTORS IN G/MILE BY CALENDAR YEAR: CALIFORNIA REGISTERED TRANSIT BUSES WITH CALIFORNIA ENGINES

Cal.	Oxides of Nitrogen (g/mile)				Unburned Hydrocarbons (g/mile)				Particulate Matter (g/mile)				Fuel Consumption (lb/mile)				Fuel Consumption (MPG)			
Year	Base	Delta	Total	% Incr.	Base	Delta	Total	% Incr.	Base	Delta	Total	% Incr.	Base	Delta	Total	% Incr.	Base	Delta	Total	% Incr.
1985	27.26	1.87	29.13	6.9%	4.38	2.11	6.49	48.0%	2.57	1.84	4.41	71.5%	1.92	0.04	1.97	2.2%	3.74	-0.08	3.66	-2.1%
1986	26.16	1.80	27.95	6.9%	4.37	2.10	6.47	48.0%	2.58	1.84	4.42	71.5%	1.92	0.04	1.96	2.2%	3.75	-0.08	3.67	-2.1%
1987	25.04	1.72	26.76	6.9%	4.36	2.09	6.45	48.0%	2.58	1.85	4.43	71.6%	1.91	0.04	1.96	2.2%	3.76	-0.08	3.68	-2.1%
1988	23.97	1.61	25.58	6.7%	4.31	2.04	6.35	47.3%	2.56	1.81	4.38	70.8%	1.90	0.04	1.94	2.2%	3.79	-0.08	3.71	-2.1%
1989	22.97	1.47	24.43	6.4%	4.22	1.94	6.15	45.9%	2.52	1.74	4.26	69.3%	1.88	0.04	1.92	2.1%	3.84	-0.08	3.76	-2.1%
1990	22.16	1.34	23.50	6.0%	4.13	1.83	5.96	44.4%	2.46	1.67	4.12	67.7%	1.85	0.04	1.89	2.1%	3.88	-0.08	3.81	-2.0%
1991	21.41	1.22	22.63	5.7%	3.99	1.73	5.72	43.5%	2.35	1.57	3.92	66.9%	1.83	0.04	1.87	2.0%	3.93	-0.08	3.86	-2.0%
1992	20.68	1.12	21.81	5.4%	3.79	1.63	5.42	43.0%	2.19	1.46	3.65	66.9%	1.81	0.03	1.84	1.9%	3.98	-0.07	3.90	-1.9%
1993	20.18	1.04	21.22	5.1%	3.60	1.53	5.13	42.4%	2.03	1.36	3.39	67.0%	1.78	0.03	1.82	1.8%	4.04	-0.07	3.96	-1.8%
1994	19.91	0.97	20.88	4.9%	3.41	1.43	4.84	41.9%	1.87	1.26	3.13	67.1%	1.75	0.03	1.78	1.7%	4.11	-0.07	4.04	-1.7%
1995	19.66	0.90	20.55	4.6%	3.22	1.33	4.55	41.4%	1.72	1.16	2.88	67.3%	1.72	0.03	1.75	1.6%	4.18	-0.07	4.11	-1.6%
1996	19.43	0.83	20.26	4.3%	3.03	1.24	4.27	40.9%	1.57	1.07	2.64	67.6%	1.69	0.03	1.72	1.5%	4.26	-0.06	4.19	-1.5%
1997	19.30	0.77	20.07	4.0%	2.84	1.14	3.99	40.2%	1.42	0.97	2.39	68.0%	1.66	0.02	1.68	1.4%	4.34	-0.06	4.27	-1.4%
1998	19.15	0.71	19.87	3.7%	2.65	1.05	3.70	39.5%	1.27	0.87	2.14	68.4%	1.63	0.02	1.65	1.3%	4.41	-0.06	4.35	-1.3%
1999	18.93	0.65	19.58	3.4%	2.47	0.96	3.43	38.7%	1.11	0.77	1.88	68.9%	1.61	0.02	1.63	1.2%	4.47	-0.05	4.41	-1.2%
2000	18.84	0.59	19.43	3.1%	2.29	0.86	3.15	37.6%	0.96	0.67	1.64	69.6%	1.59	0.02	1.61	1.1%	4.53	-0.06	4.48	-1.1%

TABLE 7-15. FLEET AVERAGE EMISSION FACTORS IN G/MILE BY CALENDAR YEAR: CALIFORNIA REGISTERED TRANSIT BUSES WITH FEDERAL ENGINES

Cal.	Oxides of Nitrogen (g/mile)				Unburned Hydrocarbons (g/mile)				Particulate Matter (g/mile)				Fuel Consumption (lb/mile)				Fuel Consumption (MPG)			
Year	Base	Delta	Total	% Incr.	Base	Delta	Total	% Incr.	Base	Delta	Total	% Incr.	Base	Delta	Total	% Incr.	Base	Delta	Total	% Incr.
1985	35.87	0.11	35.98	0.3%	4.38	1.88	6.26	42.8%	2.39	1.60	3.99	66.8%	1.83	0.05	1.89	2.8%	3.93	-0.11	3.82	-2.8%
1986	35.79	0.10	35.89	0.3%	4.37	1.87	6.25	42.8%	2.39	1.59	3.98	66.8%	1.82	0.05	1.87	2.8%	3.96	-0.11	3.85	-2.8%
1987	35.68	0.10	35.78	0.3%	4.36	1.87	6.23	42.8%	2.38	1.59	3.97	66.8%	1.80	0.05	1.85	2.8%	4.00	-0.11	3.89	-2.8%
1988	35.37	0.11	35.47	0.3%	4.31	1.82	6.13	42.2%	2.34	1.55	3.89	66.1%	1.78	0.05	1.83	2.8%	4.05	-0.11	3.94	-2.7%
1989	34.87	0.11	34.98	0.3%	4.22	1.73	5.95	41.0%	2.27	1.47	3.74	64.8%	1.76	0.05	1.80	2.7%	4.10	-0.11	3.99	-2.6%
1990	34.36	0.11	34.48	0.3%	4.13	1.64	5.77	39.7%	2.20	1.39	3.59	63.4%	1.73	0.05	1.78	2.6%	4.15	-0.11	4.05	-2.5%
1991	33.52	0.13	33.65	0.4%	3.99	1.55	5.54	38.9%	2.09	1.31	3.40	62.7%	1.71	0.04	1.76	2.5%	4.20	-0.10	4.10	-2.4%
1992	32.34	0.15	32.49	0.5%	3.79	1.46	5.25	38.5%	1.95	1.22	3.18	62.6%	1.69	0.04	1.73	2.4%	4.25	-0.10	4.15	-2.3%
1993	31.16	0.18	31.33	0.6%	3.60	1.37	4.97	38.0%	1.81	1.13	2.95	62.5%	1.67	0.04	1.71	2.2%	4.30	-0.09	4.21	-2.2%
1994	29.97	0.20	30.17	0.7%	3.41	1.28	4.69	37.6%	1.68	1.05	2.72	62.5%	1.65	0.03	1.69	2.1%	4.35	-0.09	4.26	-2.1%
1995	28.79	0.23	29.01	0.8%	3.22	1.19	4.42	37.1%	1.54	0.96	2.49	62.4%	1.63	0.03	1.67	2.0%	4.41	-0.09	4.32	-1.9%
1996	27.61	0.25	27.86	0.9%	3.03	1.11	4.14	36.6%	1.40	0.87	2.27	62.3%	1.61	0.03	1.64	1.8%	4.46	-0.08	4.38	-1.8%
1997	26.44	0.28	26.72	1.0%	2.84	1.02	3.86	36.0%	1.26	0.78	2.05	62.2%	1.60	0.03	1.62	1.7%	4.51	-0.08	4.43	-1.7%
1998	25.29	0.30	25.59	1.2%	2.65	0.94	3.59	35.3%	1.12	0.70	1.82	62.0%	1.58	0.02	1.60	1.6%	4.56	-0.07	4.49	-1.5%
1999	24.15	0.32	24.48	1.3%	2.47	0.85	3.32	34.5%	0.99	0.61	1.60	61.9%	1.57	0.02	1.59	1.4%	4.60	-0.06	4.53	-1.4%
2000	23.03	0.35	23.38	1.5%	2.29	0.77	3.05	33.6%	0.86	0.53	1.38	61.7%	1.56	0.02	1.57	1.3%	4.63	-0.06	4.57	-1.3%

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baseline emissions, however. Thus, excess emissions as a percentage of baseline emissions will increase considerably--to more than 300 percent for some classes--by the year 2000.

7.4 Fleet Average Emission Factors: All Classes Combined

By weighting the class-average emission factors in Tables 7-5 through 7-15 with the estimated VMT per day for each class, it is possible to calculate fleet-average emissions factors for each calendar year for all heavy-duty diesel truck classes combined. The resulting combined-average emissions factors are listd in Table 7-16. These factors are directly comparable to the similar fleet-average emission factors generated by models such as EMFAC7C and MOBILE3. These combined-average emission emission factors are not used in our model (instead, the class-average factors are used directly to calculate emissions). They are presented here as a matter of interest, and for the possible convenience of the user in calculating emissions from heavy-duty diesel VMT data which have not been broken down by class.

7.5 Comparison with Other Emission Factor Estimates

A number of estimates and databases of in-use emission factors for heavy-duty diesel vehicles have been developed. ARB's emission inventory is based on one set of emission factor estimates. In addition, EPA (Braddock and Perry, 1986) and SWRI (Ullman and Hare, 1985) have made chassis dynamometer measurements of emissions from a few small sets of vehicles. Finally, as discussed in Volume III, the New York City Department of Environmental Protection has measured emissions from hundreds of buses and city-owned trucks.

ARB Emission Inventory--ARB's current emission inventory for heavy-duty diesel vehicles is based on emission factors calculated by ARB's EMFAC7c model. This model uses essentially the same approach as EPA's MOBILE3 model, but includes the effects of California emission standards. This model differs somewhat in approach from the model developed by Radian. In EMFAC7c, all

TABLE 7-16. EMISSIONS PER MILE, AVERAGE OF ALL HEAVY-DUTY CLASSES

Cal. Year	Oxides of Nitrogen (g/mile) Base	Delta	Total	% Incr.	Unburned Hydrocarbons (g/mile) Base	Delta	Total	% Incr.	Particulate Matter (g/mile) Base	Delta	Total	% Incr.	Fuel Consumption (MPG) Base	Delta	Total	% Incr.
1985	21.4	1.2	22.6	5.7%	2.6	1.6	4.2	59.3%	2.2	3.0	5.2	132.2%	5.66	-0.21	5.45	-3.6%
1986	20.4	1.1	21.5	5.6%	2.6	1.5	4.1	59.3%	2.2	2.9	5.1	131.5%	5.87	-0.21	5.66	-3.6%
1987	19.7	1.1	20.8	5.6%	2.5	1.5	4.0	58.1%	2.2	2.9	5.0	131.7%	6.04	-0.22	5.82	-3.6%
1988	19.2	1.1	20.3	5.9%	2.4	1.4	3.8	58.6%	2.1	2.7	4.7	130.3%	6.23	-0.22	6.01	-3.5%
1989	18.8	1.2	20.0	6.3%	2.3	1.3	3.6	58.4%	1.9	2.5	4.4	128.7%	6.43	-0.22	6.21	-3.4%
1990	18.1	1.2	19.3	6.6%	2.2	1.3	3.4	57.9%	1.8	2.3	4.2	126.6%	6.62	-0.22	6.40	-3.4%
1991	17.3	1.3	18.6	7.5%	2.0	1.2	3.2	60.6%	1.7	2.2	3.9	129.4%	6.76	-0.21	6.56	-3.1%
1992	16.5	1.4	17.9	8.4%	1.8	1.2	3.0	64.2%	1.5	2.0	3.5	133.4%	6.90	-0.19	6.71	-2.8%
1993	15.8	1.5	17.3	9.2%	1.7	1.1	2.8	66.1%	1.3	1.8	3.2	138.0%	7.02	-0.18	6.85	-2.5%
1994	15.3	1.5	16.8	10.0%	1.5	1.1	2.6	73.0%	1.2	1.7	2.9	146.4%	7.15	-0.15	6.99	-2.2%
1995	14.7	1.6	16.3	10.8%	1.3	1.1	2.4	78.6%	1.0	1.6	2.6	157.2%	7.29	-0.13	7.15	-1.8%
1996	14.3	1.6	15.9	11.5%	1.2	1.0	2.3	84.9%	0.9	1.5	2.3	170.0%	7.40	-0.11	7.29	-1.5%
1997	13.9	1.7	15.6	12.1%	1.1	1.0	2.1	91.1%	0.7	1.4	2.1	184.6%	7.51	-0.09	7.42	-1.2%
1998	13.6	1.7	15.4	12.6%	1.0	1.0	2.0	97.3%	0.6	1.3	2.0	200.7%	7.60	-0.08	7.52	-1.0%
1999	13.4	1.7	15.1	13.1%	0.9	1.0	1.9	103.6%	0.6	1.2	1.8	218.6%	7.67	-0.06	7.61	-0.8%
2000	13.2	1.8	15.0	13.4%	0.9	1.0	1.8	109.5%	0.5	1.2	1.7	238.5%	7.74	-0.06	7.68	-0.7%

heavy-duty diesel vehicles are lumped together in one class. In addition, rather than adopting a constant emissions degradation factor, emissions deterioration factors in EMFAC7 increase as a function of vehicle mileage.

Table 7-17 compares the combined-average heavy-duty diesel emission factors from EMFAC7C for the years 1985, 1990, 1995, and 2000 with the corresponding combined-average emission factors from Table 7-16. As this table shows, the EMFAC7C NO_x and PM emission factors are somewhat lower than Radian's for all four calendar years. Radian's higher PM values reflect the greater deterioration factors assumed, especially in the later years. The NO_x values reflect some of the same effects, as well as Radian's estimate of the penetration of Federal engines into California-registered vehicles.

The EMFAC7C HC emission factors are lower than Radian's in the early years, but higher in the later ones. The lower initial values reflect the higher deterioration rates used by Radian. In the later years, however, Radian's analysis indicates that HC emissions should be greatly reduced, as a by-product of the effort to control particulate emissions (Weaver and Klausmeier, 1987). EMFAC7 does not account for this reduction.

EPA and SWRI Studies--Braddock and Perry (1986) reported the results of EPA chassis dynamometer measurements on light-heavy and medium-heavy duty diesel vehicles of model years 1977-1984. The results of these measurements are summarized in Table 7-18, along with the corresponding emission factor estimates (for 1981) from Radian's model. As this table shows, there is good general agreement with the light-heavy duty measurements, but significant differences in fuel economy and HC emissions for the medium-heavy trucks. These differences are probably due to truck size and turbocharging: Braddock and Perry tested MVMA Class VI trucks with naturally-aspirated engines, while Radian's model is more reflective of turbocharged engines in classes VII and VIII(a).

TABLE 7-17. COMPARISON OF RADIAN FLEET-AVERAGE EMISSION FACTOR ESTIMATES WITH EMFAC7C

Calendar Year	EMFAC7C[1]	Radian Average of All Classes
<u>1985</u>		
NOx	19.52	22.6
HC	3.02	4.2
PM	2.63	5.2
<u>1990</u>		
NOx	16.90	19.3
HC	2.72	3.4
PM	2.35	4.2
<u>1995</u>		
NOx	15.82	16.3
HC	2.61	2.4
PM	1.66	2.6
<u>2000</u>		
NOx	13.46	15.0
HC	2.51	1.8
PM	1.29	1.7

[1] Source: EMFAC7C pred. for California, April 6, 1986.

TABLE 7-18. COMPARISON OF RADIAN EMISSION FACTOR ESTIMATES WITH LABORATORY MEASUREMENTS

	NOx (g/mi)	HC (g/mi)	PM (g/mi)	FE (mpg)
Light-Heavy				
Braddock and Perry (3 trucks)				
Min	3.30	0.45	0.422	12.65
Mean	4.64	1.68	0.723	14.15
Max	6.46	4.11	1.202	15.80
Radian Model (MY 81)	4.40	1.42	1.18	13.58
Medium-Heavy				
Braddock and Perry (5 trucks)				
Min	7.32	2.24	0.666	9.48
Mean	9.28	3.90	1.37	9.98
Max	11.41	6.24	1.941	10.89
NYCDEP Database				
Min	19.40	1.98	1.28	2.75
Mean	37.25	4.54	2.46	4.40
Max	81.64	15.18	6.92	7.70
Radian Model (MY 81)	21.33	4.32	4.61	5.5
Transit Bus				
Ullman and Hare				
Min	15.31	1.19	1.63	4.94
Mean	18.92	1.92	2.70	5.16
Max	22.43	2.74	3.89	5.45
NYC DEP Database				
Min	25.22	4.16	1.28	1.90
Mean	55.82	8.35	4.26	2.93
Max	124.77	29.52	16.89	4.44
Radian Model (MY 81)	36.04	6.27	4.00	3.83

Sources: Braddock and Perry (1986)
Ullman and Hare (1985)

Table 7-18 also compares the results of Radian's model with Ullman and Hare's measurements on transit buses, using a chassis version of the heavy-duty transient cycle. The SWRI measurements are generally comparable to, but somewhat lower than, Radian's predictions. This is largely due to the engines in these buses--DDA Silver 6V-92TAs--and to their relatively good mechanical condition.

NYCDEP Database--Summary statistics for the buses and trucks included in this database are also given in Table 7-18. These data are discussed in greater detail in Volume III, Section 6.0. The data for buses on the New York 2 bus cycle are generally comparable, but show both higher emissions and higher fuel consumption than Radian's model, reflecting the more severe stop-and-go nature of the New York Bus 2 test cycle.

The data for trucks on the New York City truck cycle are also fairly comparable, although they show lower PM and higher NO_x than on Radian's model. It is worth noting that the trucks in the NYCDEP database exhibited average smoke emissions much lower than those observed in our visual smoke survey, and would thus be expected to have lower average HC and PM levels as well. The fact that the average emissions values in this relatively clean fleet are fairly comparable to our estimates of average overall emission factors suggests that our estimates may be slightly conservative--i.e., that we may be underestimating the actual extent of emissions degradation.

8.0 EMISSIONS MODEL RESULTS: TOTAL EMISSIONS

In order to calculate aggregate emissions, the emission factors presented in Chapter Seven must be combined with estimates of the transportation activity (vehicle-miles travelled or VMT) statewide and in critical air-pollution areas. The development of the VMT estimates used in this model is described in Section 4.3. This section presents the results obtained by multiplying these VMT estimates by the emission factors for each class. These results include calculations of baseline, excess, and total pollutant emissions by heavy-duty diesels, statewide and in each critical air-pollution area. A breakdown of statewide emissions by vehicle class is also presented.

8.1 Statewide Emissions Results

Table 8-1 displays the calculated emissions totals for the entire state, including all heavy-duty vehicle classes. Figures 8-1, 8-2, and 8-3 display the same information in graphical form. As this table indicates, the emissions impacts of tampering and malmaintenance in heavy-duty vehicles are projected to be quite significant. Tampering and malmaintenance are projected to increase particulate emissions from heavy-duty diesels by 132-239 percent, HC emissions by 60-110 percent, and NO_x emissions by about 6-13 percent statewide, depending on the specific year considered. Fuel consumption is also projected to be increased by 0.7 to 3.8 percent. Excess emissions as a percentage of the total are projected to increase somewhat over the period from 1985 to 2000.

The absolute increases in emissions due to tampering and malmaintenance are quite significant. The model projects that more than 74 additional tons of diesel particulate matter, 29 tons of NO_x, and 39 tons of hydrocarbons per day will be emitted in California in 1987 as a result of tampering with and malmaintenance of heavy-duty diesel engines. Total emissions of these pollutants are calculated as 543 tons of NO_x, 105 tons of hydrocarbons, and 131 tons of particulate matter per day. These values represent a significant fraction of the total statewide inventory of these pollutants. In the

TABLE 8-1. TOTAL EMISSIONS, ALL HEAVY-DUTY VEHICLE CLASSES: STATEWIDE

Calendar Year	Oxides of Nitrogen (TPD)				Unburned Hydrocarbons (TPD)				Particulate Matter (TPD)				Fuel Consumption (MM Gal/Yr)			
	Base	Delta	Total	% Incr.	Base	Delta	Total	% Incr.	Base	Delta	Total	% Incr.	Base	Delta	Total	% Incr.
1985	483.3	27.6	510.9	5.7%	59.5	35.3	94.8	59.3%	50.6	67.0	117.6	132.2%	1,322.7	49.8	1,372.5	3.8%
1986	510.9	28.6	539.5	5.6%	64.3	38.1	102.3	59.3%	54.8	72.2	127.0	131.6%	1,415.5	52.8	1,468.3	3.7%
1987	514.1	28.5	542.7	5.6%	65.6	38.8	104.5	59.1%	56.5	74.4	130.8	131.7%	1,432.3	53.5	1,485.8	3.7%
1988	520.9	30.9	551.8	5.9%	65.2	38.3	103.6	58.6%	55.7	72.6	128.3	130.3%	1,443.8	52.7	1,496.4	3.6%
1989	529.0	33.5	562.5	6.3%	64.4	37.6	102.0	58.4%	54.5	70.1	124.5	128.7%	1,451.9	51.6	1,503.4	3.6%
1990	529.8	35.2	565.0	6.6%	63.8	36.9	100.7	57.9%	53.9	68.3	122.2	126.8%	1,461.0	50.7	1,511.7	3.5%
1991	523.0	39.1	562.1	7.5%	60.5	36.7	97.2	60.6%	50.5	65.3	115.7	129.4%	1,481.7	46.9	1,528.5	3.2%
1992	511.0	42.7	553.8	8.4%	56.4	36.2	92.5	64.2%	46.2	61.6	107.8	133.4%	1,487.5	42.4	1,529.8	2.9%
1993	502.0	46.1	548.1	9.2%	52.7	35.9	88.6	68.1%	42.3	58.4	100.8	138.0%	1,494.8	38.5	1,533.2	2.6%
1994	495.8	49.4	545.1	10.0%	48.7	35.6	84.3	73.0%	37.8	55.4	93.2	146.4%	1,502.4	33.3	1,535.7	2.2%
1995	487.7	52.6	540.3	10.8%	44.7	35.2	79.9	78.6%	33.2	52.2	85.4	157.2%	1,507.2	27.9	1,535.1	1.9%
1996	483.7	55.4	539.2	11.5%	41.3	35.1	76.4	84.9%	29.2	49.7	78.9	170.0%	1,516.4	23.2	1,539.6	1.5%
1997	482.9	58.2	541.2	12.1%	38.5	35.1	73.6	91.1%	25.9	47.9	73.8	184.8%	1,530.0	19.3	1,549.4	1.3%
1998	483.9	60.9	544.8	12.6%	36.2	35.3	71.5	97.3%	23.0	46.3	69.3	200.7%	1,547.4	16.0	1,563.4	1.0%
1999	485.9	63.4	549.3	13.1%	34.3	35.5	69.8	103.6%	20.6	45.1	65.6	218.9%	1,566.7	13.2	1,579.9	0.8%
2000	489.5	65.8	555.3	13.4%	32.7	35.9	68.6	109.5%	18.6	44.2	62.8	238.5%	1,588.2	10.7	1,598.9	0.7%

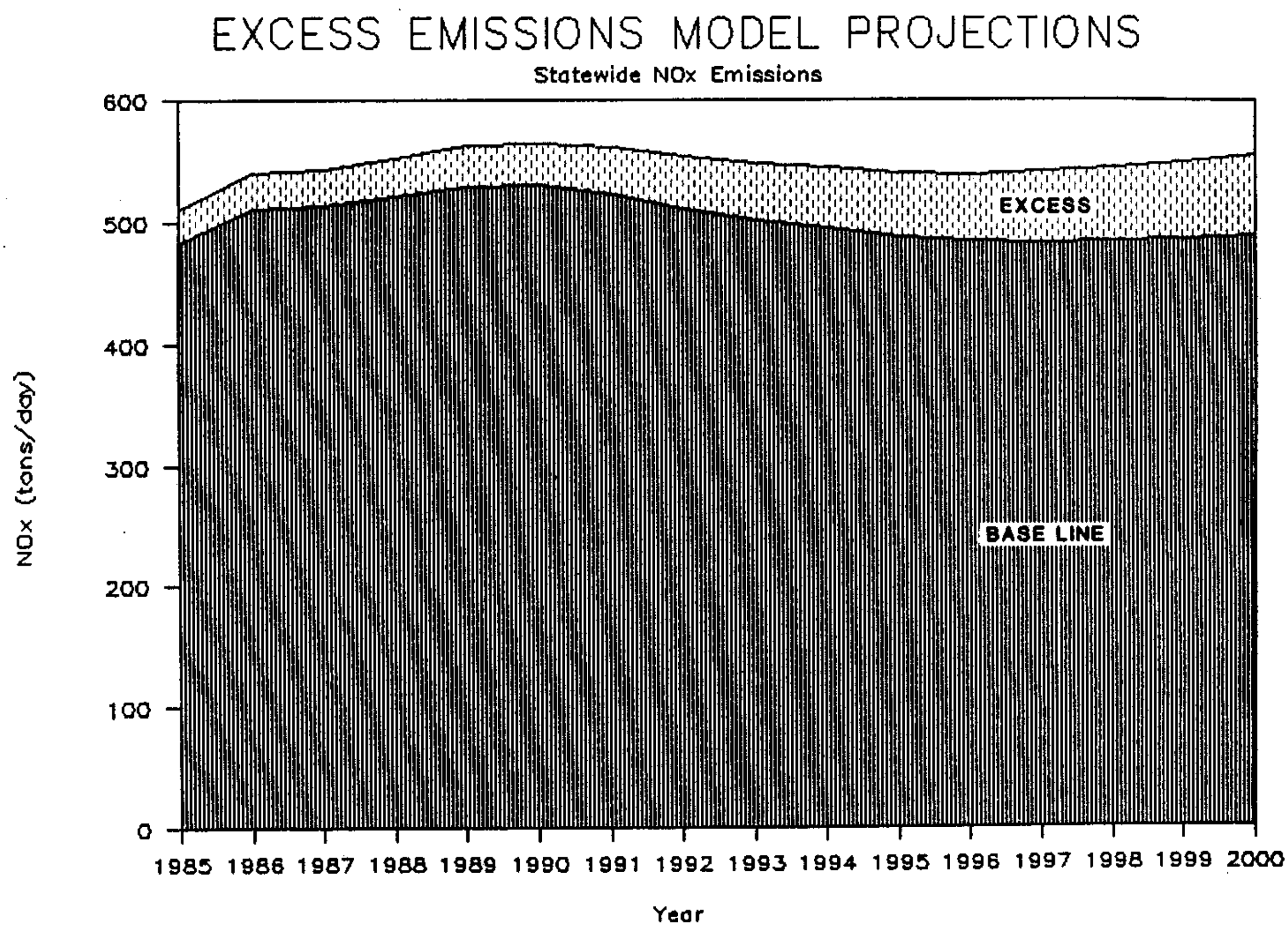

Figure 8-1. Projected Statewide NO_x Emissions from Heavy-Duty Vehicles

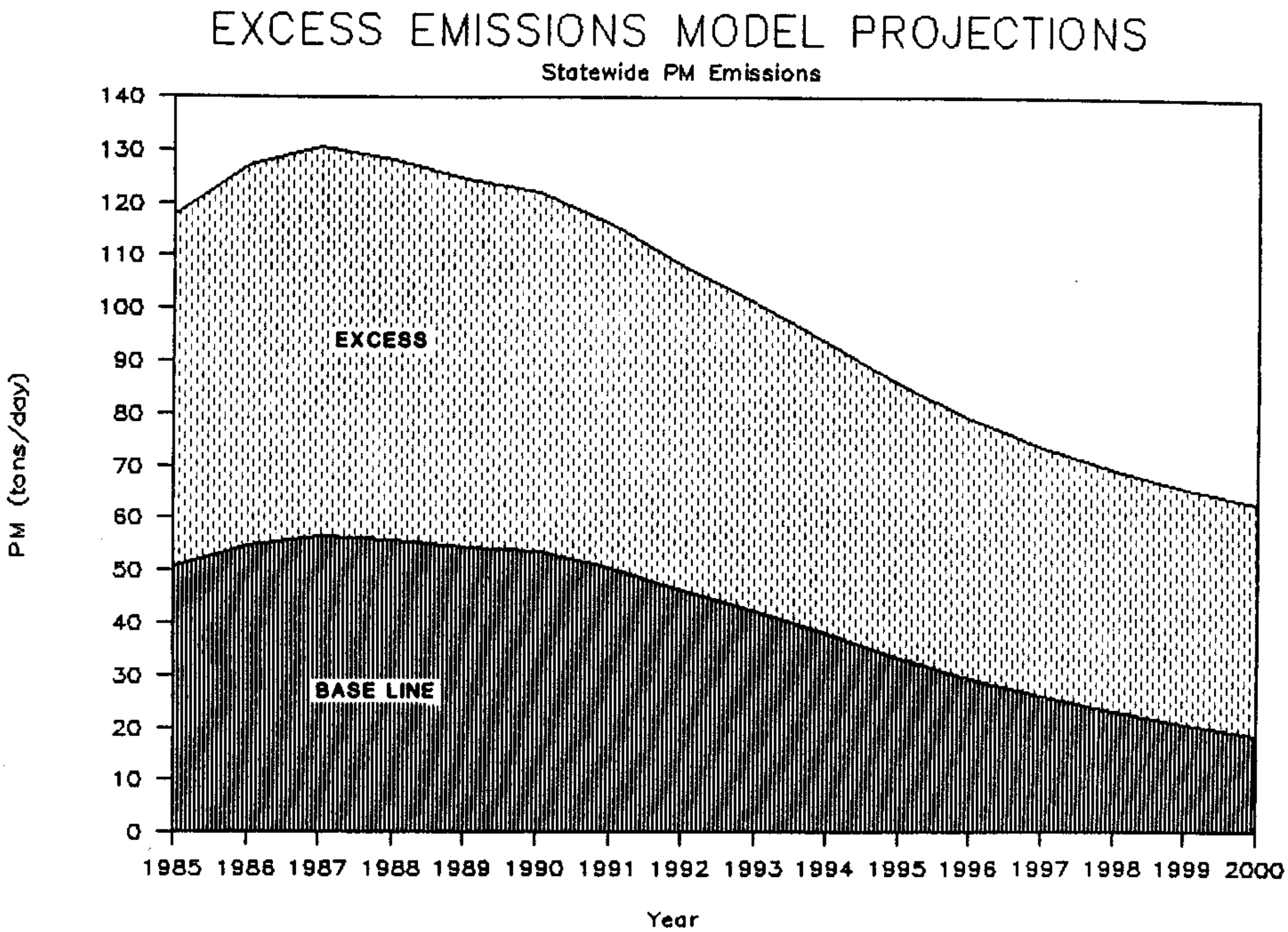

Figure 8-3. Projected Statewide PM Emissions from Heavy-Duty Diesel Vehicles

future, heavy-duty diesel NO_x and HC emissions are projected to remain roughly the same, but PM emissions will decline to about half their present level, as stringent new particulate emissions standards begin to come into effect.

The statewide emissions estimates shown in Table 8-1 may exaggerate the situation slightly, since they are based on emission factors from the Federal Transient test, which basically simulates urban operation. Particulate and HC emission factors for rural operation would probably be somewhat lower. Most of the critical air-pollution areas in the State are essentially urban, however, so that the emission factors used are appropriate for estimating the impacts on these areas. Urban VMT also account for nearly half of the total VMT statewide.

Tables 8-2 and 8-3 show the contributions made by each vehicle class to total emissions and excess emissions statewide. Data are presented for two years: 1987 and 2000. As these tables indicate, in-state vehicles are responsible for about 75-80 percent of both total and excess emissions in both years, with out-of-state vehicles accounting for about 20-25 percent. This reflects both the greater number of in-state vehicles and the generally better maintenance of out-of-state trucks (most of which are heavy-heavy tractors engaged in long-haul trucking). About half of both the total and the excess emissions in each year are from vehicles with California-model engines, with about half of those (or one quarter of the total) coming from heavy-heavy trucks. The remaining 25-30 percent of total and excess emissions are due to California-registered trucks with Federal engines, most of which are in the heavy-heavy duty class.

As Tables 8-2 and 8-3 show, the contribution of transit buses to total statewide emissions is not large compared to the other groups. This is not surprising, considering their small numbers. Due to their tendency to operate preferentially in the most congested areas of cities, the real significance of emissions from transit buses is greater than these figures would

TABLE 8-2. CONTRIBUTIONS OF EACH HEAVY-DUTY CLASS TO TOTAL STATEWIDE EMISSIONS

CONTRIBUTIONS TO TOTAL STATEWIDE EMISSIONS: 1987

	California Registered			Out-Of-		
	Calif. Engine	Federal Engine	Total	State Vehicles	Total	Percent
Oxides of Nitrogen (TPD)						
Heavy	111.7	133.7	245.4	92.5	337.9	62.3%
Medium	87.2	30.8	118.0	41.6	159.6	29.4%
Light	4.9	0.6	5.4	0.2	5.6	1.0%
Bus	16.9	22.7	39.6	0.0	39.6	7.3%
Total	220.7	187.7	408.4	134.3	542.7	100.0%
Percent	40.7%	34.6%	75.3%	24.7%	100.0%	
Unburned Hydrocarbons (TPD)						
Heavy	23.0	21.4	44.4	12.9	57.3	54.9%
Medium	24.3	6.4	30.8	8.6	39.4	37.7%
Light	1.6	0.2	1.8	0.1	1.8	1.7%
Bus	4.1	1.9	5.9	0.0	5.9	5.7%
Total	53.0	29.9	82.9	21.6	104.5	100.0%
Percent	50.7%	28.7%	79.4%	20.6%	100.0%	
Particulate Matter (TPD)						
Heavy	36.0	29.3	65.3	17.4	82.7	63.2%
Medium	27.3	6.5	33.9	8.8	42.6	32.6%
Light	1.3	0.2	1.4	0.0	1.5	1.1%
Bus	2.8	1.2	4.0	0.0	4.0	3.0%
Total	67.4	37.2	104.6	26.2	130.8	100.0%
Percent	51.5%	28.4%	80.0%	20.0%	100.0%	

(Continued)

TABLE 8-2. (Continued)

CONTRIBUTIONS TO TOTAL STATEWIDE EMISSIONS: 2000

	California Registered			Out-Of-		
	Calif. Engine	Federal Engine	Total	State Vehicles	Total	Percent
Oxides of Nitrogen (TPD)						
Heavy	128.6	137.1	265.8	87.6	353.4	63.6%
Medium	97.1	26.7	123.8	33.4	157.2	28.3%
Light	14.2	1.8	16.0	0.5	16.5	3.0%
Bus	12.8	15.4	28.2	0.0	28.2	5.1%
Total	252.8	181.0	433.7	121.5	555.3	100.0%
Percent	45.5%	32.6%	78.1%	21.9%	100.0%	
Unburned Hydrocarbons (TPD)						
Heavy	14.9	13.8	28.7	7.3	36.1	52.6%
Medium	16.5	4.4	20.8	5.4	26.3	38.3%
Light	2.6	0.3	2.9	0.1	3.0	4.4%
Bus	2.2	1.0	3.3	0.0	3.3	4.8%
Total	36.2	19.5	55.8	12.8	68.6	100.0%
Percent	52.8%	28.5%	81.3%	18.7%	100.0%	
Particulate Matter (TPD)						
Heavy	16.8	15.2	32.0	7.8	39.9	63.5%
Medium	12.1	3.1	15.3	3.9	19.2	30.6%
Light	1.9	0.2	2.1	0.1	2.1	3.4%
Bus	1.1	0.5	1.6	0.0	1.6	2.5%
Total	31.9	19.1	50.9	11.8	62.8	100.0%
Percent	50.8%	30.4%	81.2%	18.8%	100.0%	

TABLE 8-3. CONTRIBUTIONS OF TOTAL EXCESS EMISSIONS BY EACH HEAVY-DUTY VEHICLE CLASS

CONTRIBUTIONS TO STATEWIDE EXCESS EMISSIONS: 1987

	California Registered			Out-Of-State		
	Calif. Engine	Federal Engine	Total	Vehicles	Total	Percent
Oxides of Nitrogen (TPD)						
Heavy	10.7	3.5	14.3	2.8	17.1	59.8%
Medium	7.6	1.1	8.7	1.6	10.3	36.1%
Light	0.0	0.0	0.0	0.0	0.0	0.0%
Bus	1.1	0.1	1.2	0.0	1.2	4.1%
Total	19.4	4.7	24.2	4.4	28.5	100.0%
Percent	68.0%	16.6%	84.6%	15.4%	100.0%	
Unburned Hydrocarbons (TPD)						
Heavy	8.8	7.3	16.1	3.1	19.2	49.6%
Medium	10.5	2.8	13.2	3.6	16.9	43.5%
Light	0.7	0.1	0.8	0.0	0.8	2.1%
Bus	1.3	0.6	1.9	0.0	1.9	4.8%
Total	21.3	10.7	32.0	6.8	38.8	100.0%
Percent	55.0%	27.5%	82.5%	17.5%	100.0%	
Particulate Matter (TPD)						
Heavy	21.8	16.9	38.7	8.8	47.5	63.9%
Medium	15.5	3.8	19.3	5.1	24.4	32.9%
Light	0.6	0.1	0.7	0.0	0.7	1.0%
Bus	1.2	0.5	1.6	0.0	1.6	2.2%
Total	39.1	21.3	60.4	13.9	74.4	100.0%
Percent	52.6%	28.7%	81.2%	18.8%	100.0%	

(Continued)

TABLE 8-3. (Continued)

CONTRIBUTIONS TO STATEWIDE EXCESS EMISSIONS: 2000

	California Registered			Out-Of-		
	Calif. Engine	Federal Engine	Total	State Vehicles	Total	Percent
Oxides of Nitrogen (TPD)						
Heavy	16.2	19.2	35.3	12.5	47.9	72.8%
Medium	10.0	2.6	12.5	3.3	15.8	24.0%
Light	1.3	0.2	1.4	0.0	1.5	2.3%
Bus	0.4	0.2	0.6	0.0	0.6	0.9%
Total	27.8	22.1	50.0	15.8	65.8	100.0%
Percent	42.3%	33.6%	75.9%	24.1%	100.0%	
Unburned Hydrocarbons (TPD)						
Heavy	8.0	6.8	14.8	2.9	17.7	49.3%
Medium	9.7	2.6	12.2	3.1	15.4	42.8%
Light	1.5	0.2	1.7	0.1	1.8	4.9%
Bus	0.7	0.3	1.0	0.0	1.0	2.9%
Total	19.9	9.9	29.8	6.1	35.9	100.0%
Percent	55.4%	27.7%	83.0%	17.0%	100.0%	
Particulate Matter (TPD)						
Heavy	12.0	10.8	22.8	5.0	27.9	63.0%
Medium	8.9	2.3	11.2	2.9	14.1	32.0%
Light	1.3	0.2	1.5	0.0	1.5	3.5%
Bus	0.5	0.2	0.7	0.0	0.7	1.5%
Total	22.7	13.5	36.3	8.0	44.2	100.0%
Percent	51.4%	30.5%	82.0%	18.0%	100.0%	

indicate. Buses are a much more significant factor in the critical urban air pollution areas such as the South Coast and San Francisco Bay Area AQMDs.

8.2 Regional Results: Emissions In Critical Air-Pollution Areas

Tables 8-4 through 8-13 show the model results for the critical air-pollution areas in California. These areas include the South Coast, San Francisco Bay Area, and Lake Tahoe air basins; Sacramento and its surrounding area; and a number of individual counties which have not attained state or Federal air-quality standards. Not surprisingly, the area most affected by diesel emissions (as by most other types of emissions) is the South Coast Air Basin, which contains Los Angeles. This area receives about 30 percent of the total diesel emissions statewide. According to the model calculations, tampering with and malmaintenance of heavy-duty diesel engines resulted in excess emissions of 8 tons of NO_x, 21 tons of particulate matter, and over 11 tons of hydrocarbons per day in the South Coast Air Basin in 1987. The results for other air basins are generally proportional to these values, although the individual impacts on the other basins are typically much lower.

As discussed above, the model may overestimate somewhat the impacts of heavy-duty HC and particulate emissions on mostly-rural areas, since the emission factors used are more appropriate for urban operation. This overestimate would have the greatest effect on the areas along the I-5 and I-80 corridors, since these have the largest number of rural heavy-duty diesel VMT. Critical air-pollution areas along these corridors include the Sacramento Metropolitan area, and San Joaquin, Fresno, and Kern counties.

TABLE 8-4. TOTAL EMISSIONS, ALL HEAVY-DUTY VEHICLE CLASSES: SOUTH COAST AQMD

Calendar Year	Oxides of Nitrogen (TPD)				Unburned Hydrocarbons (TPD)				Particulate Matter (TPD)				Fuel Consumption (MM Gal/Yr)			
	Base	Delta	Total	% Incr.	Base	Delta	Total	% Incr.	Base	Delta	Total	% Incr.	Base	Delta	Total	% Incr.
1985	144.1	8.0	152.1	5.6%	17.6	10.4	28.0	59.0%	14.7	19.2	33.9	130.4%	376.3	14.1	390.4	3.7%
1986	148.7	8.1	156.8	5.4%	18.6	11.0	29.5	59.0%	15.6	20.2	35.7	129.6%	393.7	14.6	408.3	3.7%
1987	148.2	8.0	156.2	5.4%	18.8	11.1	29.9	59.0%	15.9	20.6	36.5	129.6%	395.9	14.7	410.6	3.7%
1988	148.8	8.6	157.4	5.7%	18.5	10.9	29.4	58.7%	15.6	20.0	35.6	128.5%	396.9	14.3	411.3	3.6%
1989	150.0	9.2	159.2	6.1%	18.2	10.6	28.8	58.3%	15.1	19.2	34.4	126.6%	397.2	14.0	411.1	3.5%
1990	149.4	9.6	158.9	6.4%	17.9	10.4	28.3	57.9%	14.9	18.6	33.5	125.0%	397.8	13.7	411.5	3.4%
1991	146.7	10.6	157.3	7.2%	17.0	10.3	27.2	60.5%	13.9	17.7	31.7	127.6%	401.6	12.6	414.2	3.1%
1992	142.5	11.4	153.9	8.0%	15.7	10.1	25.8	63.9%	12.7	16.7	29.3	131.5%	401.0	11.3	412.4	2.8%
1993	139.2	12.2	151.4	8.8%	14.6	9.9	24.6	67.7%	11.6	15.7	27.3	136.1%	400.9	10.3	411.2	2.6%
1994	136.7	13.0	149.7	9.5%	13.5	9.8	23.3	72.4%	10.3	14.8	25.1	144.1%	401.0	8.9	409.9	2.2%
1995	133.8	13.8	147.6	10.3%	12.4	9.6	22.0	77.6%	9.0	13.9	22.9	154.5%	400.5	7.4	407.9	1.8%
1996	132.1	14.4	146.6	10.9%	11.4	9.5	20.9	83.6%	7.9	13.2	21.1	166.8%	401.1	6.2	407.3	1.5%
1997	131.2	15.1	146.2	11.5%	10.6	9.5	20.0	89.5%	7.0	12.6	19.6	180.7%	402.5	5.2	407.7	1.3%
1998	130.7	15.7	146.4	12.0%	9.9	9.5	19.4	95.4%	6.2	12.1	18.3	196.3%	405.1	4.3	409.4	1.1%
1999	130.5	16.3	146.8	12.5%	9.3	9.5	18.8	101.4%	5.5	11.8	17.3	213.9%	408.2	3.5	411.8	0.9%
2000	130.8	16.8	147.6	12.8%	8.9	9.5	18.4	107.1%	4.9	11.5	16.4	232.9%	411.9	2.9	414.8	0.7%

TABLE 8-6. TOTAL EMISSIONS, ALL HEAVY-DUTY VEHICLE CLASSES: BAY AREA AQMD

Calendar Year	Oxides of Nitrogen (TPD)				Unburned Hydrocarbons (TPD)				Particulate Matter (TPD)				Fuel Consumption (MM Gal/Yr)			
	Base	Delta	Total	% Incr.	Base	Delta	Total	% Incr.	Base	Delta	Total	% Incr.	Base	Delta	Total	% Incr.
1985	73.6	4.0	77.6	5.4%	8.8	5.1	13.9	57.5%	7.4	9.6	17.0	130.1%	187.7	7.1	194.8	3.8%
1986	74.4	4.0	78.4	5.3%	9.1	5.2	14.4	57.5%	7.7	9.9	17.6	129.3%	191.7	7.2	198.9	3.8%
1987	74.6	3.9	78.5	5.3%	9.3	5.3	14.6	57.4%	7.9	10.2	18.1	129.6%	193.7	7.3	201.1	3.8%
1988	75.3	4.3	79.6	5.7%	9.2	5.3	14.5	57.1%	7.8	9.9	17.7	128.3%	195.1	7.2	202.3	3.7%
1989	76.1	4.6	80.7	6.1%	9.1	5.2	14.2	56.7%	7.6	9.6	17.2	126.6%	195.9	7.0	203.0	3.6%
1990	76.0	4.8	80.8	6.4%	9.0	5.1	14.0	56.3%	7.5	9.3	16.8	124.6%	196.9	6.9	203.8	3.5%
1991	74.6	5.4	80.1	7.2%	8.5	5.0	13.5	58.7%	7.0	8.9	15.9	127.2%	199.4	6.4	205.8	3.2%
1992	72.8	5.8	78.6	8.0%	7.9	4.9	12.8	62.0%	6.4	8.4	14.8	130.8%	199.7	5.7	205.4	2.9%
1993	71.2	6.3	77.5	8.8%	7.4	4.8	12.2	65.5%	5.8	7.8	13.6	135.0%	200.1	5.2	205.3	2.6%
1994	70.1	6.7	76.8	9.6%	6.8	4.8	11.6	70.0%	5.2	7.5	12.7	142.9%	200.7	4.5	205.1	2.2%
1995	68.7	7.1	75.8	10.4%	6.3	4.7	11.0	75.3%	4.6	7.0	11.6	153.0%	200.8	3.7	204.5	1.8%
1996	67.8	7.5	75.3	11.0%	5.8	4.7	10.5	80.8%	4.0	6.7	10.7	164.9%	201.4	3.1	204.5	1.5%
1997	67.5	7.8	75.3	11.6%	5.4	4.7	10.0	86.8%	3.6	6.4	10.0	178.5%	202.5	2.5	205.1	1.3%
1998	67.3	8.2	75.4	12.1%	5.0	4.7	9.7	92.3%	3.2	6.2	9.4	193.7%	204.1	2.1	206.2	1.0%
1999	67.2	8.5	75.7	12.6%	4.7	4.7	9.4	98.1%	2.8	6.0	8.8	210.9%	206.0	1.7	207.7	0.8%
2000	67.5	8.8	76.2	13.0%	4.5	4.7	9.2	103.7%	2.5	5.8	8.4	228.4%	208.1	1.4	209.5	0.7%

TABLE 8-6. TOTAL EMISSIONS, ALL HEAVY-DUTY VEHICLE CLASSES: METRO SACRAMENTO

Calendar	Oxides of Nitrogen (TPD)				Unburned Hydrocarbons (TPD)				Particulate Matter (TPD)				Fuel Consumption (MM Gal/Yr)			
Year	Base	Delta	Total	% Incr.	Base	Delta	Total	% Incr.	Base	Delta	Total	% Incr.	Base	Delta	Total	% Incr.
1985	21.5	1.2	22.8	5.6%	2.6	1.6	4.2	59.3%	2.3	3.0	5.3	133.1%	59.7	2.3	62.0	3.8%
1986	23.9	1.3	25.2	5.6%	3.0	1.8	4.8	59.2%	2.6	3.4	6.0	132.4%	66.9	2.5	69.4	3.8%
1987	24.2	1.4	25.6	5.8%	3.1	1.8	4.9	58.0%	2.7	3.5	6.2	132.5%	68.1	2.6	70.7	3.8%
1988	24.7	1.5	26.1	6.0%	3.1	1.8	4.9	58.7%	2.7	3.5	6.1	131.2%	69.1	2.5	71.6	3.7%
1989	25.2	1.6	26.8	6.4%	3.1	1.8	4.9	59.2%	2.6	3.4	6.0	128.5%	69.9	2.5	72.4	3.6%
1990	25.4	1.7	27.1	6.7%	3.1	1.8	4.8	57.8%	2.6	3.3	5.9	127.6%	70.7	2.5	73.2	3.5%
1991	25.2	1.9	27.1	7.6%	2.9	1.8	4.7	60.5%	2.4	3.2	5.6	130.2%	72.1	2.3	74.4	3.2%
1992	24.8	2.1	26.9	8.5%	2.7	1.7	4.5	64.1%	2.3	3.0	5.3	134.1%	72.8	2.1	74.9	2.9%
1993	24.5	2.3	26.8	9.3%	2.6	1.7	4.3	66.0%	2.1	2.9	5.0	138.7%	73.6	1.9	75.5	2.6%
1994	24.3	2.5	26.8	10.1%	2.4	1.7	4.1	73.0%	1.9	2.7	4.6	147.2%	74.4	1.7	76.0	2.2%
1995	24.0	2.6	26.7	11.0%	2.2	1.7	3.9	78.8%	1.6	2.6	4.2	158.2%	75.0	1.4	76.4	1.8%
1996	24.0	2.8	26.8	11.7%	2.0	1.7	3.8	85.0%	1.5	2.5	3.9	171.1%	75.8	1.2	77.0	1.5%
1997	24.1	3.0	27.0	12.3%	1.9	1.7	3.7	91.4%	1.3	2.4	3.7	185.9%	76.9	1.0	77.9	1.3%
1998	24.3	3.1	27.4	12.8%	1.8	1.8	3.6	97.7%	1.2	2.3	3.5	202.2%	78.2	0.8	79.0	1.0%
1999	24.5	3.3	27.7	13.3%	1.7	1.8	3.5	104.0%	1.0	2.3	3.3	220.5%	79.6	0.7	80.3	0.8%
2000	24.8	3.4	28.2	13.7%	1.6	1.8	3.5	110.0%	0.9	2.3	3.2	240.2%	81.1	0.5	81.7	0.7%

TABLE 8-7. TOTAL EMISSIONS, ALL HEAVY-DUTY VEHICLE CLASSES: FRESNO COUNTY

Calendar Year	Oxides of Nitrogen (TPD)				Unburned Hydrocarbons (TPD)				Particulate Matter (TPD)				Fuel Consumption (MM Gal/Yr)			
	Base	Delta	Total	% Incr.	Base	Delta	Total	% Incr.	Base	Delta	Total	% Incr.	Base	Delta	Total	% Incr.
1985	16.7	1.0	17.7	5.6%	2.1	1.2	3.3	59.3%	1.8	2.4	4.2	133.6%	47.1	1.8	48.9	3.8%
1986	18.3	1.0	19.4	5.7%	2.3	1.4	3.7	59.1%	2.0	2.7	4.7	132.9%	52.2	2.0	54.1	3.8%
1987	18.5	1.0	19.8	5.6%	2.4	1.4	3.8	58.6%	2.1	2.7	4.8	133.0%	52.9	2.0	54.9	3.6%
1988	18.8	1.1	20.0	6.0%	2.4	1.4	3.7	58.6%	2.0	2.7	4.7	131.7%	53.4	2.0	55.3	3.7%
1989	19.2	1.2	20.4	6.5%	2.3	1.4	3.7	58.1%	2.0	2.6	4.6	130.0%	53.7	1.9	55.6	3.6%
1990	19.2	1.3	20.5	6.8%	2.3	1.3	3.6	57.7%	2.0	2.5	4.5	128.1%	54.1	1.9	56.0	3.5%
1991	19.0	1.5	20.5	7.7%	2.2	1.3	3.5	60.4%	1.9	2.4	4.3	130.7%	54.9	1.8	56.7	3.2%
1992	18.6	1.6	20.2	8.6%	2.0	1.3	3.3	64.0%	1.7	2.3	4.0	134.6%	55.2	1.6	56.8	2.9%
1993	18.3	1.7	20.0	9.5%	1.9	1.3	3.2	68.0%	1.6	2.2	3.7	139.2%	55.5	1.4	56.9	2.6%
1994	18.1	1.9	19.9	10.3%	1.8	1.3	3.1	73.0%	1.4	2.1	3.4	147.6%	55.8	1.2	57.0	2.2%
1995	17.8	2.0	19.8	11.2%	1.6	1.3	2.9	79.0%	1.2	1.9	3.2	158.9%	56.0	1.0	57.0	1.8%
1996	17.6	2.1	19.7	11.9%	1.5	1.3	2.8	85.2%	1.1	1.8	2.9	172.1%	56.4	0.9	57.2	1.5%
1997	17.6	2.2	19.8	12.5%	1.4	1.3	2.7	91.7%	0.9	1.8	2.7	187.0%	56.9	0.7	57.6	1.2%
1998	17.7	2.3	20.0	13.0%	1.3	1.3	2.6	98.2%	0.8	1.7	2.6	203.5%	57.6	0.6	58.1	1.0%
1999	17.7	2.4	20.1	13.6%	1.2	1.3	2.5	104.6%	0.8	1.7	2.4	222.0%	58.3	0.5	58.8	0.8%
2000	17.9	2.5	20.4	13.9%	1.2	1.3	2.5	110.7%	0.7	1.6	2.3	241.9%	59.1	0.4	59.5	0.6%

TABLE 8-8. TOTAL EMISSIONS, ALL HEAVY-DUTY VEHICLE CLASSES: KERN COUNTY

Calendar	Oxides of Nitrogen (TPD)				Unburned Hydrocarbons (TPD)				Particulate Matter (TPD)				Fuel Consumption (MM Gal/Yr)			
Year	Base	Delta	Total	% Incr.	Base	Delta	Total	% Incr.	Base	Delta	Total	% Incr.	Base	Delta	Total	% Incr.
1985	23.7	1.4	25.1	5.9%	2.9	1.7	4.6	59.0%	2.5	3.4	6.0	134.3%	67.6	2.6	70.2	3.8%
1986	25.4	1.4	26.8	5.7%	3.2	1.9	5.1	58.6%	2.8	3.7	6.5	133.7%	73.2	2.8	76.0	3.8%
1987	25.6	1.5	27.2	5.7%	3.3	1.9	5.2	58.6%	2.9	3.9	6.8	133.8%	74.4	2.9	77.3	3.9%
1988	26.3	1.6	27.9	6.1%	3.3	1.9	5.2	58.2%	2.9	3.8	6.7	132.4%	75.3	2.8	78.1	3.7%
1989	26.9	1.8	28.7	6.6%	3.3	1.9	5.1	57.7%	2.8	3.7	6.5	130.6%	76.0	2.8	78.8	3.6%
1990	27.1	1.9	28.9	6.9%	3.2	1.9	5.1	57.3%	2.8	3.6	6.4	128.9%	76.8	2.7	79.5	3.5%
1991	26.8	2.1	28.9	7.8%	3.1	1.8	4.9	60.0%	2.6	3.4	6.1	131.4%	78.1	2.5	80.6	3.2%
1992	26.3	2.3	28.6	8.6%	2.9	1.8	4.7	63.6%	2.4	3.3	5.7	135.3%	78.6	2.3	80.9	2.9%
1993	25.9	2.5	28.4	9.7%	2.7	1.8	4.5	67.5%	2.2	3.1	5.3	139.6%	79.2	2.1	81.3	2.6%
1994	25.6	2.7	28.3	10.5%	2.5	1.8	4.3	72.6%	2.0	2.9	4.9	146.4%	79.8	1.8	81.6	2.2%
1995	25.3	2.9	28.1	11.4%	2.3	1.8	4.1	78.7%	1.7	2.8	4.5	159.7%	80.3	1.5	81.7	1.8%
1996	25.1	3.0	28.2	12.1%	2.1	1.8	3.9	85.0%	1.5	2.7	4.2	173.0%	80.9	1.2	82.1	1.5%
1997	25.1	3.2	28.3	12.8%	2.0	1.8	3.8	91.6%	1.4	2.6	3.9	186.1%	81.9	1.0	82.9	1.2%
1998	25.2	3.4	28.6	13.3%	1.9	1.8	3.7	98.2%	1.2	2.5	3.7	204.8%	82.9	0.9	83.8	1.0%
1999	25.4	3.5	28.9	13.8%	1.8	1.8	3.6	104.7%	1.1	2.4	3.5	223.5%	84.1	0.7	84.8	0.8%
2000	25.7	3.7	29.3	14.3%	1.7	1.8	3.5	110.9%	1.0	2.4	3.4	243.5%	85.4	0.5	85.9	0.6%

TABLE 8-9. TOTAL EMISSIONS, ALL HEAVY-DUTY VEHICLE CLASSES: SAN DIEGO COUNTY

Calendar Year	Oxides of Nitrogen (TPD)				Unburned Hydrocarbons (TPD)				Particulate Matter (TPD)				Fuel Consumption (MM Gal/Yr)			
	Base	Delta	Total	% Incr.	Base	Delta	Total	% Incr.	Base	Delta	Total	% Incr.	Base	Delta	Total	% Incr.
1985	20.4	1.2	21.6	5.9%	2.6	1.6	4.1	61.0%	2.1	2.8	4.9	131.1%	55.7	2.0	57.7	3.7%
1986	22.8	1.3	24.1	5.7%	2.9	1.8	4.7	61.0%	2.5	3.2	5.8	130.3%	63.3	2.3	65.6	3.6%
1987	22.9	1.3	24.2	5.6%	3.0	1.8	4.8	60.9%	2.5	3.3	5.8	130.5%	64.2	2.3	66.5	3.6%
1988	23.2	1.4	24.6	5.9%	3.0	1.8	4.8	60.6%	2.5	3.2	5.7	129.1%	64.8	2.3	67.1	3.5%
1989	23.6	1.5	25.1	6.3%	2.9	1.8	4.7	60.2%	2.4	3.1	5.6	127.5%	65.3	2.3	67.6	3.4%
1990	23.7	1.5	25.2	6.5%	2.9	1.7	4.6	59.6%	2.4	3.0	5.5	125.6%	65.9	2.2	68.1	3.4%
1991	23.5	1.7	25.2	7.3%	2.8	1.7	4.5	62.6%	2.3	2.9	5.2	128.4%	66.9	2.1	69.0	3.1%
1992	23.0	1.9	24.9	8.1%	2.6	1.7	4.3	66.3%	2.1	2.8	4.9	132.7%	67.5	1.8	69.3	2.6%
1993	22.7	2.0	24.7	8.9%	2.4	1.7	4.1	70.6%	1.9	2.6	4.6	137.6%	68.0	1.7	69.8	2.5%
1994	22.5	2.2	24.7	9.6%	2.3	1.7	4.0	75.4%	1.7	2.5	4.2	146.3%	68.6	1.5	70.1	2.2%
1995	22.3	2.3	24.6	10.3%	2.1	1.7	3.8	81.2%	1.5	2.4	3.9	157.1%	69.1	1.3	70.4	1.9%
1996	22.2	2.4	24.6	11.0%	1.9	1.7	3.6	87.3%	1.3	2.3	3.6	169.9%	69.8	1.1	70.9	1.6%
1997	22.3	2.6	24.9	11.6%	1.8	1.7	3.5	93.6%	1.2	2.2	3.4	184.5%	70.8	0.9	71.7	1.3%
1998	22.4	2.7	25.1	12.0%	1.7	1.7	3.4	99.6%	1.1	2.1	3.2	200.7%	71.9	0.8	72.7	1.1%
1999	22.6	2.8	25.4	12.4%	1.6	1.7	3.4	106.0%	1.0	2.1	3.0	219.0%	73.1	0.7	73.8	0.9%
2000	22.9	2.9	25.8	12.6%	1.6	1.6	3.3	111.9%	0.9	2.1	2.9	238.6%	74.4	0.6	75.0	0.8%

TABLE 8-10. TOTAL EMISSIONS, ALL HEAVY-DUTY VEHICLE CLASSES: SAN JOAQUIN COUNTY

Calendar Year	Oxides of Nitrogen (TPD)				Unburned Hydrocarbons (TPD)				Particulate Matter (TPD)				Fuel Consumption (MM Gal/Yr)			
	Base	Delta	Total	% Incr.	Base	Delta	Total	% Incr.	Base	Delta	Total	% Incr.	Base	Delta	Total	% Incr.
1985	12.7	0.7	13.4	5.8%	1.6	0.9	2.5	59.4%	1.4	1.8	3.2	134.1%	36.1	1.4	37.5	3.8%
1986	14.6	0.8	15.5	5.7%	1.9	1.1	2.9	59.2%	1.6	2.2	3.8	133.5%	42.3	1.6	43.9	3.6%
1987	14.9	0.9	15.8	5.7%	1.9	1.1	3.0	59.0%	1.7	2.2	3.9	133.6%	43.1	1.6	44.8	3.8%
1988	15.3	0.9	16.2	6.1%	1.9	1.1	3.0	58.7%	1.7	2.2	3.9	132.2%	43.9	1.6	45.5	3.7%
1989	15.7	1.0	16.7	6.5%	1.9	1.1	3.0	59.2%	1.6	2.1	3.8	130.6%	44.4	1.6	46.0	3.6%
1990	15.8	1.1	16.9	6.9%	1.9	1.1	3.0	57.7%	1.6	2.1	3.7	128.7%	45.0	1.6	46.6	3.5%
1991	15.7	1.2	16.9	7.6%	1.8	1.1	2.9	60.5%	1.5	2.0	3.6	131.3%	45.9	1.5	47.4	3.2%
1992	15.5	1.4	16.9	8.7%	1.7	1.1	2.8	64.1%	1.4	1.9	3.3	135.2%	46.4	1.3	47.8	2.9%
1993	15.3	1.6	16.9	9.6%	1.6	1.1	2.7	68.1%	1.3	1.8	3.1	138.9%	47.0	1.2	48.2	2.6%
1994	15.2	1.6	16.8	10.4%	1.5	1.1	2.6	73.2%	1.2	1.7	2.9	148.5%	47.6	1.1	48.8	2.2%
1995	15.1	1.7	16.8	11.3%	1.4	1.1	2.5	79.3%	1.0	1.7	2.7	159.6%	48.0	0.9	48.9	1.8%
1996	15.1	1.8	16.9	12.0%	1.3	1.1	2.4	85.7%	0.9	1.6	2.5	173.1%	48.6	0.7	49.3	1.5%
1997	15.1	1.9	17.1	12.7%	1.2	1.1	2.3	92.3%	0.8	1.5	2.4	188.2%	49.4	0.6	50.0	1.2%
1998	15.3	2.0	17.3	13.2%	1.1	1.1	2.2	98.8%	0.7	1.5	2.2	204.9%	50.2	0.5	50.7	1.0%
1999	15.4	2.1	17.6	13.7%	1.1	1.1	2.2	105.3%	0.7	1.5	2.1	223.6%	51.2	0.4	51.6	0.8%
2000	15.7	2.2	17.9	14.1%	1.0	1.1	2.2	111.5%	0.6	1.5	2.1	243.7%	52.2	0.3	52.5	0.6%

TABLE 8-11. TOTAL EMISSIONS, ALL HEAVY-DUTY VEHICLE CLASSES: SANTA BARBARA COUNTY

Calendar Year	Oxides of Nitrogen (TPD)				Unburned Hydrocarbons (TPD)				Particulate Matter (TPD)				Fuel Consumption (MM Gal/Yr)			
	Base	Delta	Total	% Incr.	Base	Delta	Total	% Incr.	Base	Delta	Total	% Incr.	Base	Delta	Total	% Incr.
1985	5.5	0.3	5.8	5.9%	0.7	0.4	1.1	60.4%	0.6	0.8	1.4	133.7%	15.8	0.6	16.4	3.7%
1986	5.9	0.3	6.3	5.6%	0.8	0.5	1.2	60.3%	0.7	0.9	1.5	132.9%	17.2	0.6	17.8	3.7%
1987	5.9	0.3	6.3	5.7%	0.8	0.5	1.2	60.1%	0.7	0.9	1.6	133.1%	17.2	0.6	17.8	3.7%
1988	6.0	0.4	6.3	6.1%	0.8	0.5	1.2	59.8%	0.7	0.9	1.5	131.7%	17.2	0.6	17.8	3.6%
1989	6.0	0.4	6.4	6.5%	0.7	0.4	1.2	59.3%	0.6	0.8	1.5	130.0%	17.1	0.6	17.7	3.5%
1990	6.0	0.4	6.4	6.8%	0.7	0.4	1.2	58.9%	0.6	0.8	1.4	128.1%	17.1	0.6	17.7	3.5%
1991	5.9	0.4	6.3	7.7%	0.7	0.4	1.1	61.7%	0.6	0.8	1.3	130.9%	17.2	0.5	17.7	3.2%
1992	5.7	0.5	6.2	8.6%	0.6	0.4	1.0	65.5%	0.5	0.7	1.2	135.0%	17.1	0.5	17.6	2.8%
1993	5.5	0.5	6.1	9.4%	0.6	0.4	1.0	68.6%	0.5	0.7	1.1	139.9%	17.0	0.4	17.5	2.6%
1994	5.4	0.6	6.0	10.2%	0.5	0.4	0.9	74.6%	0.4	0.6	1.0	148.6%	17.0	0.4	17.4	2.2%
1995	5.3	0.6	5.9	11.1%	0.5	0.4	0.9	80.8%	0.4	0.6	0.9	159.9%	16.9	0.3	17.2	1.6%
1996	5.2	0.6	5.8	11.7%	0.4	0.4	0.8	87.2%	0.3	0.6	0.9	173.2%	16.8	0.3	17.1	1.5%
1997	5.2	0.6	5.8	12.4%	0.4	0.4	0.8	93.9%	0.3	0.5	0.8	188.4%	16.9	0.2	17.1	1.3%
1998	5.1	0.7	5.8	12.9%	0.4	0.4	0.8	100.3%	0.2	0.5	0.7	205.1%	16.9	0.2	17.1	1.0%
1999	5.1	0.7	5.8	13.4%	0.4	0.4	0.7	106.6%	0.2	0.5	0.7	223.8%	17.0	0.1	17.1	0.8%
2000	5.1	0.7	5.8	13.7%	0.3	0.4	0.7	113.0%	0.2	0.5	0.7	244.1%	17.1	0.1	17.2	0.7%

TABLE 8-12. TOTAL EMISSIONS, ALL HEAVY-DUTY VEHICLE CLASSES: VENTURA COUNTY

Calendar	Oxides of Nitrogen (TPD)				Unburned Hydrocarbons (TPD)				Particulate Matter (TPD)				Fuel Consumption (MM Gal/Yr)			
Year	Base	Delta	Total	% Incr.	Base	Delta	Total	% Incr.	Base	Delta	Total	% Incr.	Base	Delta	Total	% Incr.
1985	8.0	0.5	8.4	5.9%	1.0	0.6	1.6	60.9%	0.8	1.1	2.0	132.6%	22.4	0.8	23.2	3.7%
1986	8.2	0.5	8.7	5.8%	1.0	0.6	1.7	60.9%	0.9	1.2	2.1	132.1%	23.4	0.9	24.2	3.7%
1987	8.2	0.5	8.7	5.7%	1.1	0.7	1.7	60.8%	0.9	1.2	2.1	132.2%	23.7	0.9	24.6	3.7%
1988	8.3	0.5	8.8	6.1%	1.1	0.6	1.7	60.4%	0.9	1.2	2.1	130.6%	23.8	0.9	24.7	3.6%
1989	8.5	0.5	9.0	6.4%	1.0	0.6	1.7	60.0%	0.9	1.1	2.0	129.1%	24.0	0.8	24.8	3.5%
1990	8.5	0.6	9.1	6.7%	1.0	0.6	1.7	59.8%	0.9	1.1	2.0	127.3%	24.1	0.8	25.0	3.4%
1991	8.4	0.6	9.0	7.5%	1.0	0.6	1.6	62.4%	0.8	1.1	1.9	130.1%	24.5	0.8	25.3	3.1%
1992	8.2	0.7	8.9	8.4%	0.9	0.6	1.5	66.2%	0.8	1.0	1.8	134.3%	24.6	0.7	25.3	2.8%
1993	8.1	0.7	8.8	9.2%	0.9	0.6	1.5	70.4%	0.7	1.0	1.7	139.4%	24.8	0.6	25.4	2.6%
1994	8.0	0.8	8.8	9.9%	0.8	0.6	1.4	76.5%	0.6	0.9	1.5	148.0%	24.9	0.6	25.5	2.2%
1995	7.9	0.9	8.8	10.7%	0.7	0.6	1.3	81.5%	0.5	0.9	1.4	159.1%	25.0	0.5	25.5	1.8%
1996	7.9	0.9	8.8	11.4%	0.7	0.6	1.3	87.9%	0.5	0.9	1.3	172.4%	25.2	0.4	25.6	1.5%
1997	7.9	0.9	8.8	12.0%	0.6	0.6	1.2	94.3%	0.4	0.8	1.2	187.4%	25.5	0.3	25.8	1.3%
1998	7.9	1.0	8.9	12.5%	0.6	0.6	1.2	100.7%	0.4	0.8	1.1	204.0%	25.8	0.3	26.1	1.1%
1999	7.9	1.0	9.0	13.0%	0.6	0.6	1.2	107.1%	0.3	0.7	1.1	222.6%	26.2	0.2	26.4	0.9%
2000	8.0	1.1	9.1	13.3%	0.5	0.6	1.2	113.2%	0.3	0.7	1.0	242.8%	26.6	0.2	26.8	0.7%

TABLE 8-13. TOTAL EMISSIONS, ALL HEAVY-DUTY VEHICLE CLASSES: LAKE TAHOE

Calendar Year	Oxides of Nitrogen (TPD)				Unburned Hydrocarbons (TPD)				Particulate Matter (TPD)				Fuel Consumption (MM Gal/Yr)			
	Base	Delta	Total	% Incr.	Base	Delta	Total	% Incr.	Base	Delta	Total	% Incr.	Base	Delta	Total	% Incr.
1985	0.5	0.0	0.5	6.0%	0.1	0.0	0.1	61.9%	0.1	0.1	0.1	134.0%	1.4	0.0	1.4	3.7%
1986	0.4	0.0	0.5	5.8%	0.1	0.0	0.1	62.2%	0.1	0.1	0.1	132.6%	1.4	0.0	1.4	3.6%
1987	0.4	0.0	0.5	5.7%	0.1	0.0	0.1	62.1%	0.1	0.1	0.1	132.6%	1.4	0.0	1.4	3.6%
1988	0.5	0.0	0.5	6.0%	0.1	0.0	0.1	61.9%	0.1	0.1	0.1	131.1%	1.4	0.0	1.4	3.5%
1989	0.5	0.0	0.5	6.4%	0.1	0.0	0.1	61.5%	0.0	0.1	0.1	129.4%	1.4	0.0	1.4	3.4%
1990	0.5	0.0	0.5	6.7%	0.1	0.0	0.1	61.2%	0.0	0.1	0.1	127.4%	1.4	0.0	1.4	3.3%
1991	0.5	0.0	0.5	7.5%	0.1	0.0	0.1	64.5%	0.0	0.1	0.1	130.7%	1.4	0.0	1.5	3.0%
1992	0.4	0.0	0.5	8.4%	0.1	0.0	0.1	68.7%	0.0	0.1	0.1	135.4%	1.4	0.0	1.5	2.7%
1993	0.4	0.0	0.5	9.3%	0.0	0.0	0.1	73.3%	0.0	0.1	0.1	141.0%	1.4	0.0	1.5	2.5%
1994	0.4	0.0	0.5	10.1%	0.0	0.0	0.1	78.9%	0.0	0.1	0.1	150.2%	1.5	0.0	1.5	2.2%
1995	0.4	0.0	0.5	10.9%	0.0	0.0	0.1	85.3%	0.0	0.0	0.1	162.0%	1.6	0.0	1.5	1.8%
1996	0.4	0.1	0.5	11.6%	0.0	0.0	0.1	92.1%	0.0	0.0	0.1	175.9%	1.5	0.0	1.5	1.5%
1997	0.4	0.1	0.5	12.2%	0.0	0.0	0.1	99.1%	0.0	0.0	0.1	191.7%	1.5	0.0	1.5	1.3%
1998	0.4	0.1	0.5	12.7%	0.0	0.0	0.1	105.8%	0.0	0.0	0.1	209.0%	1.5	0.0	1.6	1.1%
1999	0.4	0.1	0.5	13.2%	0.0	0.0	0.1	112.5%	0.0	0.0	0.1	228.3%	1.6	0.0	1.6	0.9%
2000	0.5	0.1	0.5	13.6%	0.0	0.0	0.1	118.8%	0.0	0.0	0.1	248.9%	1.6	0.0	1.6	0.8%

9.0 SENSITIVITY AND UNCERTAINTY ANALYSIS

No mathematical model can produce "truth"--at best, a model can only systematize and calculate out the consequences of the data and assumptions which enter into it. While it is based on the best and most complete data available, the model presented in this report nonetheless includes many estimates and assumptions, and these introduce varying degrees of uncertainty into the final results. In this section, we define the major sources of this uncertainty, and evaluate the sensitivity of the model results to variations in the key assumptions.

Sources of uncertainty--Somewhat simplified, the calculation of estimated total emissions for a given class of heavy-duty vehicles is the multiplication together of five factors: the baseline emission factor (in g/BHP-hr) for well maintained vehicles; an emissions degradation factor reflecting the effects of tampering and malmaintenance; the emissions conversion factor, which has units of BHP-hr per mile; the total number of vehicle-miles travelled by heavy-duty vehicles; and the fraction of those VMT which are travelled by vehicles of the given class.

$$E = (EF)(DF)(CF)(VMT)(f) \qquad (9\text{-}1)$$

From this equation, the likely fractional uncertainty in the final results can be estimated as

$$\frac{\Delta E}{E} \cong \sqrt{\left(\frac{\Delta EF}{EF}\right)^2 + \left(\frac{\Delta DF}{DF}\right)^2 + \left(\frac{\Delta CF}{CF}\right)^2 + \left(\frac{\Delta VMT}{VMT}\right)^2 + \left(\frac{\Delta f}{f}\right)^2} \qquad (9\text{-}2)$$

where the Δs represent the likely range of uncertainty (expressed as a confidence interval) of each of the variables. Equation 9-2 would be strictly valid only if each factor in Equation 9-1 were a lognormally distributed random variable. This is not the case, since there is no possibility of repeated sampling. Although not strictly accurate, Equation 9-2 is a useful approximate guide to the uncertainty in our emissions estimates, however,

Of the five factors entering into Equation 9-1, three are considered to have low fractional uncertainty values. The data on total VMT are based on extensive research and measurement, and are considered to have a fractional uncertainty no greater than +/- 10 percent. The baseline emission factors were also based on extensive certification and other data, and are considered to be accurate to within +/- 15 percent. The emissions conversion factors were also based on plentiful technical data, but they are based on an assumed equality between emissions per unit of fuel used on the transient cycle and emissions per unit of fuel used on the road. This equality is only approximately true. We estimate the fractional uncertainty in the conversion factors to be +/- 15 percent.

Uncertainty in VMT Breakdown--The breakdown of VMT by vehicle class is based on two different sets of data. The division between light-heavy, medium-heavy, and heavy-heavy duty vehicles, and between in-state and out-of state vehicles, is based on the work of Horie and Rapoport (1985). Except for light-heavy duty vehicles, these data are considered to be fairly reliable. (Due to a methodological flaw, Horie and Rapoport probably undercounted the number of light-heavy duty vehicles). Some additional uncertainty was introduced by the need to convert from Horie and Rapoport's weight classes to ours, as discussed in Section 4.3. Overall, therefore, we estimate these weight class breakdowns to be reliable within about +/- 15 percent.

The division between California-registered vehicles with California engines and those with Federal engines is much less reliable. These were based on a "snapshot" of DMV registration data and some fairly gross assumptions, and are considered to have an uncertainty of about +/- 30 percent. Little of this uncertainty propagates through to the final results, however. A vehicle not placed in one of these classes is placed instead in another class which has similar emissions characteristics. Thus, the total emissions for all classes combined are relatively unaffected even by large shifts in the division between the classes.

To examine the sensitivity of the final results to changes in the division between vehicle classes, calculations were made with two alternate sets of data. In one set, the fraction of California-registered vehicles in each weight class having Federal engines was reduced to one-half of the baseline estimate. This changed the overall emissions numbers by zero to 4 percent, depending on the year and the pollutant in question. Estimates of excess emissions were somewhat more affected: with the changes ranging from zero to 15 percent of the total for NO_x. This is mostly due to the rather small excess NO_x emissions estimated in the model. Excess PM and HC were changed only zero to 4 percent.

In another analysis, Radian examined the uncertainty introduced by the incomplete counting of light-heavy duty VMT. For this analysis, estimated total light-heavy VMT in each year were doubled. This resulted in a zero to 4 percent increase in total emissions, and a zero to 5 percent increase in excess emissions, depending on the year and the pollutant considered.

These analyses show that the overall emissions results are quite insensitive to changes in the breakdown of diesel VMT by class. We estimate the uncertainty in the overall results introduced by possible errors in the VMT breakdown to be around +/- 5 percent.

Uncertainty in Emissions Degradation Factors--The emissions degradation factors developed in this project were based on a variety of data of widely varying quality and applicability, and their development involved considerable engineering judgement and a great many assumptions. In addition, due to the lack of applicable data, we have had only limited opportunities to check them against the real world. The limited comparisons performed in

Section 7.3 showed considerable variations, both between the data sources and our projections, and between the different data sources themselves. These limited comparisons suggest that our estimates are, if anything, somewhat conservative, but the uncertainty in these estimates must be recognized as very high. To reduce these uncertainties, further research, involving comprehensive inspections and emissions measurements on a large representative sample of heavy-duty trucks, is needed.

Our projections of degradation factors for future engines are even more uncertain than those for present-day engines. To make these projections, it was necessary to estimate tampering and failure rates for future emission control technologies, as well as the penetration of these technologies into the truck fleet. To examine the sensitivity of our results to the uncertainties in these measurements, we carried out a revised set of calculations in which the frequency of occurrence of tampering with future emissions controls was reduced to half of the baseline estimate. This change resulted in reductions of 6 percent, 9 percent, and 15 percent in total NO_x, HC, and PM, respectively, in the year 2000. Excess emissions of these pollutants were decreased by 49 percent, 17 percent, and 21 percent, respectively. The large percentage change in excess NO_x emissions reflects the low level of excess emissions projected for this pollutant, and the fact that most of these excess emissions are due to tampering.

Based on the foregoing, and the fact that we have deliberately chosen to error at all--on the conservative side, Radian estimates the uncertainty in the final excess emissions results for HC and PM due to uncertainties in our emissions degradation factors to be from -30 to +70 percent. The uncertainties in the excess NO_x calculations are considerably larger, but our data show that excess NO_x is quite small compared to the total.

Overall Uncertainty--The overall uncertainty in the final emission results can now be estimated using the approximate formula in Equation 9-2.

For the baseline emissions, the emissions degradation factor does not enter into the calculation, and the fractional uncertainty can be approximated as:

$$\frac{\Delta E_{Baseline}}{E_{Baseline}} \cong \sqrt{(0.30)^2 + (0.30)^2 + (0.2)^2 + (0.1)^2} = 0.48 \qquad (9.3)$$

or +/- 24 percent of the estimated value.

For excess emissions, which do include the emissions degradation factor, the fractional uncertainty can be approximated as:

$$\frac{\Delta E_{Excess}}{E_{Excess}} \cong \sqrt{(0.30)^2 + (1.0)^2 + (0.30)^2 + (0.2)^2 + (0.1)^2} = 1.11 \qquad (9\text{-}4)$$

The uncertainty in the emission degradation factor dominates all of the other terms. Thus, to a good approximation, the uncertainty in the overall excess emission results for HC and PM is equal to the uncertainty in the emissions degradation factors, or -30 to +70 percent. The fractional uncertainty in excess NO_x emissions is much greater than this, but these emissions are small.

Total emissions are equal to the sum of baseline and excess emissions. Their uncertainty can be calculated as:

$$\Delta E_{Total} \cong \sqrt{(\Delta E_{Baseline})^2 + (\Delta E_{Excess})^2} \qquad (9\text{-}5)$$

Table 9-1 shows the estimated uncertainties in total emissions of NO_x, HC, and PM calculated using this formula. For this calculation, the uncertainty in the excess NO_x emission factors has been estimated at -50 to + 100 percent.

TABLE 9-1. UNCERTAINTY IN TOTAL STATEWIDE EMISSIONS ESTIMATES

	Emissions (Tons Per Day, Statewide)					
	Baseline		Excess		Total	
	Best Est.	Range of Uncertainty[1]	Best Est.	Range of Uncertainty[2]	Best Est.	Range of Uncertainty[4]
NOx						
1987	514	391 - 637	29	14 - 57[3]	543	425 - 675
1990	530	403 - 657	35	18 - 70[3]	565	444 - 704
1995	488	371 - 605	53	26 - 105[3]	540	430 - 677
2000	490	372 - 607	66	33 - 132[3]	555	444 - 699
HC						
1987	66	50 - 81	39	27 - 66	104	87 - 137
1990	64	48 - 79	37	26 - 63	101	84 - 132
1995	45	34 - 55	35	25 - 60	80	66 - 108
2000	33	25 - 41	36	25 - 61	69	56 - 95
PM						
1987	57	43 - 70	74	52 - 126	131	106 - 185
1990	54	41 - 67	68	48 - 116	122	99 - 172
1995	33	25 - 41	52	37 - 89	85	69 - 123
2000	19	14 - 23	44	31 - 75	63	49 - 94

1 +/- 24 percent.
2 +70 to -30 percent.
3 +100 to -50 percent.
4 Combination of uncertainties in baseline and excess emissions, using equation 9-5.

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