RADIAN CORPORATION

DCN: 87-245-019-04

HEAVY-DUTY DIESEL VEHICLE INSPECTION AND MAINTENANCE STUDY

FINAL REPORT
VOLUME IV

I/M PROGRAM DESIGN AND COST-EFFECTIVENESS ANALYSIS

Submitted to:

California Air Resources Board
1800 15th Street
P.O. Box 2815
Sacramento, CA 95812

ARB Contract No. A4-151-32

Submitted by:

Christopher S. Weaver, P.E.
Project Director

Robert F. Klausmeier
Program Manager

Radian Corporation
10395 Old Placerville Road
Sacramento, CA 95827

May 16, 1988

RADIAN CORPORATION

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

RADIAN CORPORATION

LIST OF TABLES

LIST OF TABLES (Continued)

RADIAN CORPORATION

LIST OF TABLES (Continued)

RADIAN CORPORATION

LIST OF TABLES (Continued)

RADIAN CORPORATION

LIST OF FIGURES

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 IV. 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 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, this volume, outlines several possible designs for I/M programs using these procedures, and estimates the emissions reductions and cost-effectiveness for each.

1.3 Guide to the Remainder of Volume IV

Volume IV is divided into eight sections, of which this Introduction is the first. Section Two, following, discusses appropriate goals for a heavy-duty diesel I/M program, and describes the major design issues involved. Two major types of program designs are described, along with several variations. The effectiveness and cost-effectiveness of each program design are estimated in subsequent sections.

Section Three discusses the maintenance and repair costs for the common types of emissions-related defects in heavy-duty diesels. (These defects were discussed at length in Volume II). The results of a repair cost survey for existing technologies are presented, along with our estimates of repair costs for future technologies.

Sections Four through Eight examine the costs and effectiveness of each of the possible heavy-duty diesel I/M programs outlined in Section Two. Section Four presents our estimates of the administrative and inspection costs for each type of program. Section Five then describes a simple model of I/M program effects on the frequency of occurrence of emissions defects, repair costs, and offensive smoke. The model inputs used for each I/M scenario are also presented and discussed. Section Six describes the effects of each I/M program scenario on statewide pollutant emissions, as calculated by the excess emissions model developed in Volume II. Section Seven presents the repair costs, repair probabilities, and offensive smoke data calculated by the I/M effects model for each I/M scenario. Section Eight, finally, aggregates the repair cost and program cost estimates for each scenario to arrive at an overall cost and cost-effectiveness estimate.

1.4 Limitations and Caveats

This report presents our estimates of the effectiveness, costs, and cost-effectiveness of each of several possible heavy-duty diesel I/M programs. These estimates are heavily based on the model of excess heavy-duty diesel emissions described in Volume II. 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. The limitations on the data and assumptions going into the basic model have been discussed in Volume II.

In addition to these limitations of the model, the results presented here reflect our estimates of the effects of alternative heavy-duty diesel I/M programs. These estimates are necessarily very rough: estimates of the effectiveness even of operating I/M programs are notoriously difficult, and no programs comparable to those described here are now in operation. In the absence of hard data to serve as a benchmark, even the most careful estimates contain a great deal of uncertainty, and the estimates presented here should be understood in this light. Our estimates are based on experienced judgement, and we consider them to be somewhat conservative (in the sense of under-estimating the effects of an I/M program), but they cannot be shown to be either "right" or "wrong" based on the data available today.

Our estimates also assume that the programs described are competently designed, effectively executed, and vigorously enforced. This has not always been the case in light-duty I/M programs in the U.S. A poorly designed or badly enforced I/M program would sacrifice a large portion of the benefits estimated in this report, while costing as much or more. These limitations should be borne in mind in interpreting and applying our results.

2.0 ISSUES IN I/M PROGRAM DESIGN

Design of an inspection and maintenance program for heavy-duty diesel vehicles presents many difficult issues. Because of the differences in technology, ownership, and operating patterns, existing I/M programs for light-duty vehicles may not be a good model for heavy-duty diesel I/M. Other existing enforcement programs aimed at heavy-duty trucks, such as the weigh stations and safety inspection programs operated by the California Highway Patrol, should be considered as models as well. This section describes our suggested design goals for a heavy-duty diesel I/M program, and then examines a number of design options in the different program elements to see how they could be combined to achieve these goals. Finally, several different candidate I/M program designs are laid out. The effectiveness and cost-effectiveness of these alternative approaches are evaluated in the remainder of the report.

2.1 Program Goals and Design Criteria

The results of the excess emissions model presented in Volume II show that most excess heavy-duty diesel emissions are due to "gross emitters"--vehicles with HC and PM emissions four to 20 times the baseline--and to tampering with emission controls. By the year 2000, tampering is estimated to account for more than 50 percent of excess emissions, while gross-emitting vehicles (those with severe injector problems, excess oil consumption, or mechanical failures) will account for 30 percent. While they account for a large fraction of the total emissions, these vehicles are only a fairly small fraction of the vehicle fleet. The remaining excess emissions are generally due to poor maintenance practices--i.e. failure to perform needed maintenance which is more or less routine.

In order to effectively reduce emissions, while minimizing the burden on vehicle owners, the primary goals of a heavy-duty diesel I/M program should be the following:

- Deter tampering with emission controls;
- Detect tampering which is not deterred, and require that it be corrected;
- Identify gross-emitting vehicles, and require that they be repaired; and
- Encourage proper maintenance and awareness of the importance of emission controls in the bulk of the heavy-duty diesel fleet.

To achieve these goals and obtain public acceptance, a heavy-duty diesel I/M program will need to exhibit the following characteristics.

Effectiveness--The test procedures must effectively identify tampered or high-emitting vehicles, and the enforcement mechanism must ensure that these vehicles are repaired or otherwise brought into compliance.

Deterrence--Tampering detection must be effective enough (in terms of frequency of inspection and probability of identifying a tampered vehicle) to deter most tampering.

Fairness--The program should be perceived as fair, both by the public and by those subject to it. Errors of omission should be minimized and errors of commission must be very few.

Enforceability--Compliance with the inspection requirements and performance of any required repairs should be enforceable, preferably through existing law-enforcement structures.

Cost-effectiveness--Direct and indirect costs of the program (to the State, the affected industry, and the public) should be balanced against program benefits, and costs at a given level of effectiveness should be as small as possible

Ease of implementation and administration--The program should be consistent with existing regulatory activities, and should present no major operational or administrative problems.

2.2 I/M Program Design Options

The key design elements for an I/M program are the inspection type, inspection location, frequency of inspection, test procedures and equipment to be used, system of enforcement, and the repair requirements for failing vehicles. Models for these program elements can be found in existing programs of weight and safety inspections for heavy-duty vehicles, as well as light-duty vehicle I/M programs. Some of the the available program design options in each of these areas are discussed in this section.

2.2.1 Inspection Type and Location

Existing I/M programs are of two types: centralized and decentralized. In centralized programs, vehicles are brought to one of a relatively small number of central facilities which are dedicated to I/M testing. These facilities are usually government-owned, and may be operated either by government employees or by a government contractor. In decentralized inspection programs, such as California's Smog Check Program, inspections are performed at one of a large number of private garages equipped with emission analyzers. Vehicle fleets may also be permitted to self-inspect. Both the garage and the individual inspectors are typically required to be licensed, and their performance is typically checked by government auditors. The effectiveness of this oversight varies greatly from program to program.

Centralized I/M programs have a number of advantages. Since the number of inspection stations is typically much smaller than in a decentralized program, each station can be equipped with more extensive test equipment. By spreading the cost of expensive equipment such as dynamometers over a larger number of vehicles, these programs have the potential to be more cost-effective than decentralized programs. This advantage may be offset, however, by the greater inconvenience and time lost by the public in traveling to the stations, and then travelling back to a garage for repairs and returning to the station for a retest if the vehicle fails.

Centralized I/M programs are generally considered to be preferable from an effectiveness standpoint, although both types of programs vary considerably in this regard. Centralized programs employ a much smaller number of inspectors, who typically perform I/M inspections as their primary duty. In decentralized programs, inspections are performed by mechanics who often have many other duties. Training, oversight, and quality control of the inspections are far easier in a centralized program, and the inspectors rapidly develop considerable experience and expertise. These advantages are especially important in anti-tampering and functional inspections, which are much more dependent on the competence and honesty of the inspector than are tailpipe measurements.

Fraud and incompetence on the part of the I/M mechanics have been major problems in many decentralized I/M programs, including California's Smog Check Program. As has already been found with the Smog Check Program, stringent licensing requirements and vigorous enforcement tactics (including under-cover vehicle operations) are needed to combat these. Heavy-duty diesel mechanics are typically highly competent, and could doubtless be trained to perform inspections. Fraud could be expected to be a major problem in a heavy-duty diesel I/M program, however, due to the large sums of money involved. Recommended repair cost limits for a heavy-duty diesel I/M program range from $500 to $1,000, and the costs of repairing some forms of tampering could be several times these.

To ensure that full program benefits were obtained in a decentralized heavy-duty diesel I/M program would require a vigorous program of enforcement, including undercover vehicle operations and heavy penalties for fraud. Due to the monetary incentives involved, license revocations and fines might not be sufficient to deter fraudulent inspections: jail sentences might be required for the most flagrant cases.

Field inspection may also be a suitable I/M approach for heavy-duty diesel vehicles. The California Highway Patrol presently conducts weight and safety equipment checks at a eleven strategically located permanent inspection stations around the State, as well as unannounced weight checks at a large number of locations using portable scales. Safety inspections and review of maintenance records are also conducted at truck terminals. More than 60,000 trucks were inspected at 17,679 truck terminals in 1985 (CHP, 1986). ARB's field staff also conducts occasional checks for emission control tampering by truck fleets. About 500 trucks were inspected by ARB during fiscal years 1984-85 and 1985-86. This inspection presently concentrates on gasoline-fueled truck fleets, however.

2.2.2 Inspection Frequency and Predictability

The frequency and predictability of I/M inspections can significantly affect program costs and effectiveness. More frequent inspections help to deter tampering, and they reduce the length of time that a vehicle can run with a defect before it is detected and fixed. In traditional I/M programs, the program costs also increase with increasing inspection frequency, and a point of diminishing returns is soon reached. Most light-duty I/M programs have settled on annual inspection periods, but the California Smog Check Program uses a biennial inspection.

The high cost of frequent inspections under the traditional I/M programs is due to the need to take the vehicle to a separate location and subject it to a specific time-consuming test. An in-use inspection program conducted at weigh stations and truck depots would involve much less cost and delay per inspection, and could thus be conducted more frequently than the traditional I/M program. It would be possible, for example, to station smoke enforcement and anti-tampering inspectors at all CHP weigh stations and scales, to monitor smoke emissions from the trucks passing through on a continuous basis.

Another advantage of the in-use inspection program is its unpredictability. In traditional I/M programs, the vehicle owner knows well in advance when the vehicle is scheduled to be inspected. Given this warning, he could "untamper" with the emission controls before the inspection--resetting the puff limiter to give lower smoke, for instance, or reconnecting the trap bypass valve. The emission controls could then be restored to their former (tampered) state after the inspection. Use of smoke-suppressant additives in the fuel in order to pass a smoke opacity test would also be possible. An in-use inspection program would make such anticipatory changes difficult, unless they were maintained all the time that the truck is within the enforcement area.

2.2.3 Test Procedures and Instrumentation

The range of possible test procedures and instrumentation for a heavy-duty diesel I/M test is determined by the inspection type and location. For a centralized I/M program, the most practical test procedures are those using a dynamometer, due to the space requirements and safety concerns of the on-road tests. The relatively limited number of inspection locations, however, makes it practical to install quite sophisticated emissions measurement equipment. The trained and expert inspectors possible with this type of program are also capable of very complete functional and anti-tampering inspections.

The sophistication level of the instruments for a garage-based decentralized program is limited to that which can practically be operated and maintained (except for periodic calibration) by a typical mechanic. These programs could practically use a smoke opacity meter in conjunction with either dynamometer-based or on-road tests, and they could apply a simple, rugged emissions analyzer for dynamometer measurements. These facilities are also technically capable of carrying out an anti-tampering inspection and/or functional checks of emissions controls. Experience with the Smog Check Program has shown that these checks are often not well performed in the absence of vigorous enforcement efforts, however.

The most restrictive testing limitations apply to the in-use inspection and maintenance programs. Dynamometer-based tests are clearly impractical, and even the on-road smoke tests are time-consuming enough that it would be undesirable to apply them at random. The most practical approach to in-use smoke enforcement would be to visually screen trucks for smoke opacity using one of the on-road test procedures described in Volume III, with doubtful or disputed cases resolved by repeating the test with an opacimeter.

2.2.4 Program Enforcement and Cost Limits

Similar to existing I/M program

To be effective, an I/M program requires some means of ensuring that all vehicles subject to the program actually undergo inspection and any required maintenance. In traditional I/M programs, the most effective way of ensuring that vehicles are inspected is to require the submission of an inspection report (Smog Certificate in California) with the vehicle's annual registration. Separate windshield stickers and similar mechanisms have been found to be relatively ineffective in light-duty programs.

Compliance with an in-use inspection program would be enforced in the same way that weight and safety inspections are enforced now--a requirement that all trucks on a given road pass through the scales, where they are subject to being pulled over for an overweight citation or a safety inspection. Under the in-use program, these trucks would also be subject to being pulled over to be cited for excessive smoke, or for an anti-tampering inspection.

Most light-duty I/M programs have also adopted repair cost limits to limit the amount that a vehicle owner is required to spend to bring its emissions into line. From an emissions standpoint, these limits are generally undesirable, as they tend to focus attention on meeting the cost limit rather than fixing the problem. This is especially true if the cost limit is unrealistically low, as is the case with the $50 cost limit under the current Smog Check program. Since many of the common repairs to heavy-duty diesel engines are fairly expensive, adoption of too low a cost limit could cripple the program. We recommend that any cost limit for heavy-duty diesel be at least $500, and preferably $1000, in order to allow for realistic repairs. In the event of tampering with the emission controls, no cost limit should apply.

2.2.5 Tampering Deterrence

As the surveys reported in Volume II have shown, tampering with emission control settings on heavy-duty diesels is common now. In the absence of an effective I/M program, tampering with emission controls can be expected to be fairly common in the future as well. The costs, maintenance requirements, and adverse effects on fuel economy of many future emission control technologies will provide a strong incentive to tamper. Some of this tampering would doubtless be deterred by a good periodic I/M program. However, many potential forms of tampering with heavy-duty diesel emission controls are reasonably reversible, so that they could fairly easily be "untampered" immediately before a scheduled inspection, and restored to their former (tampered) condition immediately afterward. Examples of such reversible tampering include replacing the ROM chip in an electronic control system, "turning up" the maximum fuel rate or the smoke puff limiter, keeping a trap-oxidizer bypass valve open, and clamping an EGR line shut.

While these actions are all illegal under California law, this law is presently not enforced effectively against truck owners or operators. One effective approach to discouraging tampering would be to begin enforcing the law effectively, through a program of random anti-tampering checks at weigh stations and truck depots, with heavy fines for those caught tampering. It is important to emphasize that the economic benefits of tampering may be quite significant--savings of $1,000 to $2,000 per year in fuel and maintenance costs would be possible for a line-haul truck. The fines imposed would need to be large enough to offset this economic incentive, otherwise they will simply be treated as a cost of doing business. We recommend a fine of $1,000 for the first violation, escalating rapidly for subsequent offenses.

2.3 Selection of Alternative I/M Program Scenarios

The I/M program scenarios selected for investigation in this study consist of a number of variations on two basic approaches: a dynamometer-based periodic I/M program, and a program of in-use smoke opacity enforcement and random anti-tampering inspections. These scenarios are summarized in Table 2-1. Case 1, the basic periodic I/M scenario, consists of the following elements.

- Periodic, annual inspections enforced through the registration process.

- Decentralized, garage-based inspection program, using chassis dynamometer test procedures for smoke opacity and gaseous pollutant concentration in specific operating modes.

- Visual or functional checks of emission controls such as EGR valves, trap bypass valves, timing advance units, etc.

- Anti-tampering inspection of trap-oxidizer, catalytic converter, fuel injection system seals, etc.

- Regulations requiring fuel injection system adjustments to be sealed by an authorized shop, and making breaking the seal prima facie evidence of tampering.

TABLE 2-1. I/M SCENARIOS CONSIDERED

Case	Inspection	Frequency	Cost Limit	Gaseous Emissions ?
1	Decentralized	Annual	$1,000	Yes
1a	Centralized	Annual	1,000	Yes
1b	Decentralized	Annual	500	Yes
1c	Decentralized	Annual	None	Yes
1d	Decentralized	Annual	1,000	No
1e	Decentralized	Biennial	1,000	Yes
1f	Decentralized	Biennial	100	Yes
2	In-use	Variable	1,000	No
2a	In-use	Variable	None	No

- $1,000 cost limit for repairs, no cost limit for correcting tampering. Cost waivers require approval by a referee station.

- Overall program administrative and enforcement structure similar to the existing Smog Check, but with aggressive undercover enforcement and expanded mechanic training.

Cases 1a through 1f consist of variations on this basic scenario. In Case 1a, inspection is performed in central, state-operated inspection stations, rather than in truck garages. In Case 1b, the repair cost limit is reduced to $500. In Case 1C, the repair cost limit is eliminated--i.e. "fix it or park it". In Case 1d, the gaseous pollutant concentration measurements are eliminated, reducing the cost of the program, but also reducing its effectiveness for NO_x and HC control. Case 1e is a biennial inspection program. Case 1f, the final variation, reflects the legal constraints of the current Smog Check legislation. These include: biennial inspection, $100 cost limit, and a limit on the charge for a Smog Certificate of $6.00.

Case 2 describes a very different I/M program based on in-use smoke opacity enforcement and anti-tampering inspections. Key features of this program are the following.

- ARB Smoke Inspectors stationed at CHP truck scales and inspection stations, maintaining continuous visual screening for excessive smoke, and with the authority to pull a truck over for a smoke test and/or anti-tampering inspection.

- Trucks cited for excessive smoke must be repaired and test below the standards within two weeks, or receive a cost waiver. The cost limit for repairs is $1,000. Smoke tests after repairs may be performed by BAR-authorized garages.

- Trucks cited for excessive smoke more than once in 6 months are subject to a $250 fine (except where the first citation resulted in a waiver).

- Tampering with emission controls, or knowingly operating a truck with tampered controls, is subject to a $1,000 fine for the first offense, and $2,500 fine for each subsequent occurrence. Tampering must be corrected immediately, with no cost limit.

- ARB Inspectors to accompany CHP depot truck inspection teams in order to conduct anti-tampering inspections at the same time the CHP conducts safety inspections.

- Regulations requiring fuel injection system adjustments to be sealed by an authorized shop. Breaking the seal is prima facie evidence of tampering.

- $1,000 cost limit for repairs, no cost limit for correcting tampering. Cost waivers require approval by a referee station.

- Tightening the existing truck smoke law, training State and local police in smoke enforcement, and issuing traffic police with opacimeters.

- Dedicated roving smoke patrol officers in critical air pollution areas such as the South Coast.

A variant, Case 2a, is identical to Case 2 except that the repair cost limit of $1,000 is eliminated.

The projected costs, effectiveness, and cost-effectiveness of these alternative programs are presented in the following sections.

3.0 COST OF REPAIRS

In order to evaluate the potential effectiveness and cost-effectiveness of a heavy-duty diesel I/M program, it is important to know or estimate the costs of repairing emissions-related defects. These costs are important for three reasons.

(1) The costs of repair determine the number of vehicles receiving waivers for cost exceedance (if the program includes a repair cost limit) and thus impact the overall effectiveness of the program.

(2) High repair costs increase the motivation (and thus the potential) for cheating and corruption in the program, again impacting its overall effectiveness.

(3) Costs of repairs which would not otherwise be performed are part of the economic costs of the program, and thus help determine its cost-effectiveness.

The common types of emissions-related defects in heavy-duty diesel engines are listed in Table 3-1, along with the most likely repair action for each. Typical repair costs for current technology engines were determined by surveying heavy-duty diesel repair shops. Section 3.1 discusses the results of this survey. Estimated repair costs for future engine technologies are discussed in Section 3.2.

3.1 Repair Cost Survey

In order to determine the present costs of repairing common emissions-related defects in heavy-duty diesel engines, Radian staff contacted service personnel (e.g., service managers, shop foremen, etc.) from factory authorized service facilities for the major engine manufacturers: Caterpillar,

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

Defect	Repair
Injection Timing Changes	
Timing Retarded	Reset Timing
Timing Advanced	Reset Timing
Fuel Injection Problems	
Minor Injector Problem	Remove and clean or replace injectors
Moderate Injector Problem	Remove and clean or replace injectors
Severe Injector Problem	Remove and clean or replace injectors rebuild pump
Fuel Air Ratio Problems	
Puff Limiter Misset	Remove and recalibrate pump
Puff Limiter Disabled	Reconnect or R&R pump
Maximum Fuel Too High	Remove and recalibrate pump
Clogged Air Filter	Replace filter
Turbocharger Worn/Wrong Type	Rebuild/replace turbo
Intercooler Clogged	Remove and clean intercooler
Other Air-Supply Problems	Various (usually minor)
Other Engine Problems	
Excessive Oil Consumption	Rebuild turbo or overhaul engine
Engine Mechanical Failure	Overhaul engine
Future Technologies	
Electronic Controls Failed	Replace ECU and/or sensor(s)
Electronic Controls Tampered	Replace ECU and/or sensors
Catalytic Converter Removed	Replace catalyst
Trap Bypassed	Repair bypass valves
Trap Failed/Removed	Replace trap
EGR System Disabled	Reconnect/Replace EGR Valve

Cummins, Detroit Diesel Allison, Navistar, and Mack. The following data were requested:

(1) Cost to set injection timing to factory specifications;

(2) Costs to replace or clean fuel injectors/nozzles;

(3) Cost to repair or replace injection pumps;

(4) Cost to repair or replace air-fuel ratio controls (puff/smoke limiter);

(5) Cost to replace air filter;

(6) Cost to replace or repair turbocharger;

(7) Cost to repair or replace intercooler (where applicable);

(8) Cost to repair fuel leaks and pressure leaks;

(9) Costs of minor and major engine overhauls and costs of exchange engines;

(10) Hourly rates for mechanic's labor; and

(11) Recommended repair cost limit for an I/M program, in order to be able to cover the bulk of emissions-related repairs.

Several of the shops surveyed employed chassis dynamometers for diagnostic purposes, and some also performed diagnostic tests such as the Cummins Compucheck® or Caterpillar PARS®. These tests are roughly comparable in complexity and requirements to our proposed Periodic I/M Test procedure. To help us estimate the likely price of the PIMT, these shops were asked to provide cost data for diagnostic procedures and for dynamometer use, and to estimate their likely charges for a PIMT-type test.

Radian staff surveyed six diesel repair shops--one dealer for each of the five major U.S. manufacturers, plus one "independent" shop authorized to perform repairs on several engine makes. All of these shops repaired medium and heavy-heavy engines, but only two worked on light-heavy duty engines. Since light-heavy duty engines differ considerably from medium-heavy and heavy-heavy duty engines in complexity and technology, repair shops dealing with light-heavy duty engines were asked to provide separate data for them. The survey results for light-heavy duty engines are presented in Table 3-2, while those for medium-heavy and heavy-heavy duty engines are given in Table 3-3.

As these tables show, there is a considerable range in repair costs for specific items. This is often due to differences in engine technology. For example, adjusting the timing on a Mack or Navistar engine with an in-line pump is a far less expensive process than adjusting the injector clearances on a DDA or Cummins engine. Replacing an in-line fuel pump is far more expensive, however.

3.2 Estimated Repair Costs for Future Technologies

A number of the emissions defects listed in Table 3-1 involve emissions control technologies which are not yet in common use in heavy-duty diesel engines. These include electronic engine control systems and the associated sensors and actuators, catalytic converters, trap-oxidizers, and EGR systems. The costs of repairs to these systems were estimated by extrapolating from the costs of similar light-duty emission systems, and from previous estimates of trap-oxidizer system costs (Weaver et al., 1984). Table 3-4 shows the estimated range of costs for these items. The bases for these estimates are briefly discussed below.

TABLE 3-2. ARB DIESEL I/M PROJECT INSPECTION AND REPAIR COST SURVEY

	Navistar (IHC) 6.9L	GMC/DDA 6.2L
Timing Reset	$55	$65
Injectors Change		
Parts (ea.)	$30-35	$36.50
Labor	$130	$100-150
Injection Pump		
Part	$250-600 (Remanufactured unit)	
Labor	$130-150	$150-475
Puff Limiter	N/A	N/A
Air Filter Change		
Parts	$20	$30
Labor	$25	$10
Turbocharger	N/A Natural aspirated engine	N/A
Intercooler	N/A	N/A
Fuel Leaks		
Parts	---	---
Labor	---	---
Engine Overhaul		
Minor	$3,000-5,600	$1,800-2,200
Major	N/A	$3,800-4,500
Exchange	$5,600-6,200	$5,240
Dynamometer Use	$50-75/hr (Sublet)	$65-85/hr (Sublet)
Hourly rate	$43	$43.50
I/M Procedure Inspection Cost	$60-100	$50-100
I/M Cost Limit	$1,000	$1,000

TABLE 3-3. REPAIR COST SURVEY RESULTS FOR MEDIUM AND HEAVY-HEAVY DUTY ENGINES

	Caterpillar	Cummins	Detroit Diesel Allison (DDA)	Navistar (IHC)	Mack	Independent Caterpillar/ Cummins/DDA Authorized Serv.
Timing Reset	$90-100	$250-2500[b]	$350[f]	$50-100	$75	$200-250 (Basic Tune-up)
Injectors Change Parts (ea.) Labor	$38-56	$28-35 $350	$37-48 $350	$35-60 $125-175	$50-60 ($30-40 Tips) $75-125	$35-60 $100-200
Injection Pump Part Labor	$650-700 Remanufactured $2700 New for 3406 Engine $100-150	$150-250 Rebuilt $300-450 Exchange $150-200 Labor	$40[g] $45	Variable $90-125	$900-1000 $150 (approx.)	$200-2000[e]
Puff Limiter Parts Labor	$70 $50	$230[e]	$50-350[h] $90	— —	Variable $25-125	$100-200[e]
Air Filter Change Parts Labor	$30-80 $25	$80[e]	$45-50[e]	$30-75[e]	$100-125[e]	$100-150[e]
Pressure Leaks Labor	—	$40-80	$350[i]	$125 (Complete Pressure Check)	—	—
Turbocharger Parts Labor	$350-400 Remanufactured	$450-500 Exchange	$500-650[c]	$700-800 $125-175	$350 Cummins $500-550 Mack $50	$600-1500[e]
Intercooler Parts Labor	CAT uses air to air cooler	$270 Exchange $200 To clean $250 to R & R	$700[e]	$200 (Approx.) $85-125 to Clean $125-225 to R&R	$75 to Clean	$200-700[e] $350-500 DDA[e] $90-150 Cummins[e]
Fuel Leaks Labor Parts	$50-100 ($250-300 worst case) $37 ea. for fuel lines plus other parts as needed	$40-100 Variable	$350[i]	— —	— —	— —
Engine Overhaul Minor Major Exchange	$2500-4500[a] $4500-10,000[a] —	$2570-5435 $8,000-12,000 $9,000-15,000+	$4,000-5,000 $5,700-8,700 $7,500+	$3,900-5,280 $9,000-13,000 $15,000-16,000	$5,000 — $15,000-25,000	$6,000 — $12,000-20,000 More for 80+ Engines

(Continued)

TABLE 3-3. (Continued)

	Caterpillar	Cummins	Detroit Diesel Allison (DDA)	Navistar (IHC)	Mack	Independent Caterpillar/ Cummins/DDA Authorized Serv.
Dynamometer Use	$75 Base $125 w/Adjustments $200 PARS I[c] $400 PARS II[d]	$100/hr (approx.)	$100/hr (approx.)	$50-75/hr (Sublet)	$50-60/hr (Sublet)	$65-85/hr (Sublet)
Hourly Rate	$44	$41.50	$43	$43	$39.50	$43.50
I/M Procedure Inspection Cost	$175	$50-100	$100	$60-100	$75-100 w/o Dyno $125-150 w/Dyno	$50-100
Recommended I/M Cost Limit	$450-1000	$500-1000	$750	—	—	$1,000

— Information not provided by dealer.
a Range is due to costs of overhauling various Caterpillar engine models.
b High end of range in rate (e.g., severe tampering such as wrong cams, etc.).
c PARS—Power Analysis Report—PARS is performed on a dynamometer and compares engine performance with original engine specifications.
d PARS II is a comprehensive six-hour diagnostic procedure which checks the fuel system, HP output in various modes, turbocharger performance, injection timing, air-fuel ratio controls and numerous other items.
e Parts and labor.
f Cost for tune up. Timing set included in this procedure.
g Fuel pump cost—DDA using low pressure injection system.
h Low range is for repair of existing unit—higher range is for a new unit.
i Complete injection system pressure check and set.

TABLE 3-4. ESTIMATED RANGE OF REPAIR COSTS FOR FUTURE TECHNOLOGIES

Defect	Typical	Range
Trap-oxidizer	$500	$200-2,000
Catalytic Converter	$600	$400-1,200
Electronic Controls	$800	$400-2,000
Electric System	$150	$20-250

Electronic controls--Electronic control units for heavy-duty diesel vehicles will be comparable in functions and complexity to existing electronic controls for light-duty, spark-ignition vehicles. The greater durability and reliability required and the smaller production volumes for the diesel control systems will increase the costs considerably, however. Parts costs for electronic control units for light-duty cars range from about $170 to $700, while sensors (except airflow sensors, which are unlikely to be used on diesels) range from $20 to $200. We expect the corresponding costs for heavy-duty diesel systems to be at least double these values. With an allowance for labor, and the possibility of multiple failures, this results is the cost range shown.

Catalytic converters--Replacement converter units for autos range from about $200 to $600 in price. Converters for trucks will be much larger, and will be produced and distributed in lower volumes, which would tend to increase the cost. The catalyst material may be less expensive, however, as these units would not require rhodium for NO_x reduction. We estimate the cost for heavy-duty diesel units at 2-3 times that for catalytic converters in light-duty vehicles, or about $400-$1,200.

Trap-oxidizers--We anticipate that most trap-oxidizer system failures will not require replacing the entire system. In many cases of tampering, all that would be needed would be to reconnect or replace the bypass valve. Most other tampering and most in-use failures would require replacing the trapping element, and possibly repairing or replacing other components. The replacement parts cost of the trapping element is estimated at $200 to $500, depending on its size, to which would be added the labor to install it. Correcting tampering with the bypass valve, or a control system failure which had not damaged the trap, would be less expensive--probably $200-$300. Complete replacement of the entire system with a remanufactured one would be quite costly--probably about $1,500 to 2,000 dollars.

EGR Systems--Most EGR system problems involve disconnected or plugged lines, or EGR valve failure. The costs of EGR valves for light-duty vehicles range from about $50 to $80. Due to the greater flowrates, problems with particulate fouling, and smaller production volume, EGR valves for diesels would probably cost 2 to 3 times as much. Cleaning out a plugged line or reconnecting a disconnected one would be quite inexpensive, however.

3.3 Cost Estimates Used in The Model

The simple I/M effects model described in Section Five requires as input a set of point estimates of the average cost to repair each type of emissions defect. Separate estimates of repair costs in light-heavy duty engines and medium-heavy or heavy-heavy duty engines are required. Table 3-5 shows the cost estimates that were used for this report. These estimates were developed subjectively, based on the results of the cost survey and our estimates of repair costs for future technologies. It should be noted that these values are intended to represent averages only--actual repair costs for any one type of defect will vary considerably from engine to engine and case to case.

TABLE 3-5. ESTIMATED AVERAGE COSTS OF REPAIR FOR EMISSIONS-RELATED DEFECTS

Defect Type	Repair Cost: Medium and Heavy-Heavy	Repair Cost: Light-Heavy
Timing Advanced	$200	$60
Timing Retarded	$200	$60
Minor Inj. Problems	$300	$200
Mod. Inj. Problems	$500	$300
Severe Inj. Problems	$500	$300
Puff Lt'er Misset	$150	$100
Puff Lt'er Disabled	$200	$150
Maximum Fuel High	$400	$200
Clogged Air Filter	$70	$40
Wrong/Worn Turbo	$600	$500
Intercooler Clogged	$150	$150
Other Air Problems	$100	$80
Engine Mech. Failure	$4,000	$2,500
Excess Oil Cons.	$6,000	$4,000
Electronics Failed	$800	$600
Electronics Tampered	$400	$300
Catalyst Removed	$600	$450
Trap Removed/Bypassed	$500	$400
EGR Disabled	$150	$100

4.0 ESTIMATING PROGRAM COSTS

The costs of a heavy-duty diesel I/M program include direct costs to the vehicle owner, indirect costs to the owner, and government costs of administering and enforcing the program. The administrative and enforcement costs of the current Smog Check Program are presently funded through charges for Smog Certificates, and we have assumed that a similar arrangement would be used for a heavy-duty diesel I/M program. Thus, the government costs, too, would be borne by the vehicle owner. Since heavy-duty diesel vehicles are used almost exclusively for commercial purposes, these costs would ultimately be passed on to consumers.

The direct costs of a periodic I/M program to the vehicle owner are the costs of the I/M inspection itself (including any government charges for the Smog Certificate), the cost of making repairs, and the costs of correcting any tampering that is detected. Indirect costs include the value of the truck and driver time lost in taking the truck in for inspection, and in having the truck repaired. The costs for an in-use inspection program would fall into the same categories, except that the cost of the initial inspection would be eliminated. The imposition of a fine for tampering would add another potential cost to the vehicle owner. This is not a cost in the economic sense, however, since it represents only a transfer payment from the owner to government--no actual economic resources are consumed.

4.1 I/M Inspection Charges

In our survey of diesel repair shops discussed in Section Three, the shops were asked to estimate the likely range of charges for an I/M inspection. These estimates ranged from $50-100 for several shops up to $175 for one. As a check on these values, we estimated what a shop would need to charge in order to cover its costs and normal profit on these inspections.

Capital equipment required to perform the I/M inspection includes a chassis dynamometer and an appropriate smoke opacity meter/emissions analyzer. For our estimates, we assumed that the instrumentation would be packaged in manner similar to the Test Analyzer Systems (TAS) used in the light-duty Smog Check Program. The analyzers were assumed to cost $25,000, with a useful life of five years. The chassis dynamometer was assumed to cost $150,000 installed, with a ten year useful life. Assuming a 15 percent return on capital, this results in net capital charges of $37,500 per year. Operating costs, utilities, and other overheads were assumed to add another $7-8,000 per year to this figure.

Assuming a reasonable utilization level of five tests per day, five days per week, 50 weeks per year, these fixed costs would be spread over about 1,250 tests per year, requiring a charge of about $35 per test. In addition, about one hour of mechanic time would be required to perform the test, at an hourly rate of about $40 per hour. Thus, the overall charge for a shop to perform the test should be about $75. The costs would be somewhat lower for light-heavy duty vehicles and transit buses: the former because they can use less expensive dynamometers, and the latter because the tests would usually be performed in-house, with a greater utilization factor for the equipment.

4.2 Government Administrative and Enforcement Costs

Costs of administration and enforcement would differ, depending on the design of the I/M program and the vigor of the enforcement program. Only very rough cost estimates are possible at this point. This section presents these rough estimates for the three types of programs included in our scenarios: a decentralized periodic program, a centralized periodic program, and an in-use smoke enforcement and inspection program.

4.2.1 Decentralized Program

Table 4-1 shows the estimated annual costs of administering and enforcing a decentralized I/M program in about 1990. It was assumed that this

TABLE 4-1. ESTIMATED COST TO THE STATE OF ADMINISTRATION AND ENFORCEMENT FOR A DECENTRALIZED HEAVY-DUTY DIESEL I/M PROGRAM

Referee Facilities and Undercover Shops

Facility and Equipment	Capital Cost	Annual Cost
Building and Site	$200,000	$29,806
Dynamometer	$150,000	$22,355
Emissions Analyzer	$25,000	$6,261
Other Tools and Equipt.	$25,000	$3,726
Total Fac. and Equipt.	$400,000	$62,148
Staff (3 FTE)		$120,000
Utilities and Misc.		$30,000
Total Cost Per Facility		$212,148

Total Program Costs

Referee Facilities (15 @ $212,148)	$3,182,220
Undercover Vehicle Shops (2 @ $212,148)	$424,296
Undercover Vehicles	$200,000
Field and Management Staff (13 FTE)	$520,000
DMV Staff (3 FTE)	$120,000
Total	$4,446,516
Number of Vehicles Affected	260,000
Cost Per Vehicle	$17

program would be managed by the Bureau of Automotive Repair (BAR), and administered through existing BAR field offices. The major costs of the program would then be the capital, operating, and labor costs of referee facilities and undercover vehicle preparation shops equipped for heavy-duty diesel I/M tests. At least fifteen referee facilities would be needed to provide reasonable geographic coverage for California: four in the South Coast; two each in the Bay Area and San Diego; and one each in Bakersfield, Fresno, Stockton, Sacramento, Ventura, Redding, and Eureka. Two undercover vehicle preparation shops would also be required, one in Southern California and one in Northern California.

Each of these facilities was assumed to cost $400,000 ($200,000 for the building, land, and improvements; $150,000 for the dynamometer; $25,000 for the emissions analyzer; and $25,000 for other tools and equipment). Assuming bond financing at 8 percent and a ten year life (except for the analyzers, which have a five year life), this results in an annual capital charge of $62,148 per facility. Each facility was assumed to have a staff of three full-time equivalent people (FTE). At an average burdened cost of $40,000 per person, this adds another $120,000 per year per facility. Each facility was also assumed to have $30,000 per year in operating costs.

In addition to the costs of the referee and undercover stations, some additional BAR field and management staff and DMV staff would be required to administer the program. These were assumed to amount to 13 FTE for the BAR, and 3 FTE for DMV. Finally, the cost of purchasing and operating vehicles for undercover enforcement was assumed to be quite significant--about $200,000 per year. Thus, the net cost of the program would be about $4.4 million per year. Assuming that 260,000 heavy-duty vehicles would be subject to the program, this would require a charge of $17.00 for a Heavy-Duty Diesel Smog Certificate in order to cover program costs.

4.2.2 Centralized Program

Table 4-2 shows the estimated costs of a centralized dynamometer-based I/M inspection program for heavy-duty diesel vehicles. It was assumed

TABLE 4-2. ESTIMATED COST TO THE STATE OF INSPECTION, ADMINISTRATION, AND ENFORCEMENT FOR A CENTRALIZED HEAVY-DUTY DIESEL I/M PROGRAM

	Capital Cost	Annual Cost
Inspection Test Lanes (each)		
Facility and Equipment	Capital Cost	Annual Cost
Building and Site	$125,000	$18,629
Dynamometer	$140,000	$20,864
Emissions Analyzer	$25,000	$6,261
Other Tools and Equipt.	$10,000	$1,490
Total Fac. and Equipt.	$300,000	$47,245
Staff (4.5 FTE)		$180,000
Utilities and Misc.		$30,000
Total Program Costs		
Inspection Lanes (102 @ $257,245)		$26,238,941
Management Staff (6 FTE)		$360,000
DMV Staff (3 FTE)		$120,000
Total		$26,718,941
Inspections/Year		260,000
Cost Per Inspection		$100

that a large number of central inspection stations--equipped with variable numbers of test lanes--would be established throughout the state. Assuming an average of twelve vehicles per lane per day and six day per week operation, each test lane could handle 3,600 vehicles per year. Some 260,000 heavy-duty diesel vehicles are expected to be registered in 1990. We assumed that all of these vehicles would be inspected at least once, and that about 30% would fail and require reinspection. The resulting 338,000 inspections per year would require 95 test lanes. Allowing for some underutilization in outlying areas, we have assumed that 102 lanes would be required.

Each test lane (with accompanying building, land, parking, etc. was assumed to cost $300,000 to build and equip. This is lower than the cost of a referee station in the decentralized case, since multiple-lane facilities would allow for substantial economies of scale. The total cost for 102 lanes would then be $30.6 million. The required capital charges would be about $4.2 million per year, assuming bond financing at 8 percent and a ten year life.

A staff of 4.5 FTE (including supervisory and management personnel, and allowing for vacation and sick leave) was assumed to be required for each test lane, at a cost of $180,000 per lane per year. Some central management staff, and staff support by the DMV would also be required. Operating and miscellaneous costs of $30,000 per lane per year were also assumed.

The total annual cost for the administration, inspection, and enforcement program under this scenario would be about $26.7 million. Assuming 260,000 vehicles per year, the cost per vehicle inspected would be about $100.

4.2.3 In-Use Program

Our proposed in-use smoke enforcement program would be fairly low in cost, due to its reliance on existing inspection and enforcement mechanisms. Table 4-3 shows the costs of a very vigorous in-use enforcement program. The only capital expenditures for this program would be for about 600 recording

TABLE 4-3. INSPECTION, ENFORCEMENT, AND ADMINISTRATION COSTS OF AN IN-USE I/M PROGRAM FOR HEAVY-DUTY DIESEL VEHICLES

	Capital Cost	Annual Cost
600 Portable Recording Opacity Meters	$1,800,000	$450,822
80 ARB Smoke Inspectors and Supervisors		$3,200,000
Travel and Per-Diem Expenses		$400,000
20 Full-Time Smoke Patrol Officers (Local APCD)		$1,000,000
500 State and Local Traffic Officers @ 5% Time		$1,750,000
	Total	$6,800,822

end-of-stack opacity meters, similar to the Wager model used in the test program described in Volume II, but with additional data-processing capabilities. These were assumed to cost about $3,000 each in quantity.

This program would include 80 full-time ARB smoke and anti-tampering inspectors (including supervisors and managers) posted at Highway Patrol weigh stations and inspection stations, and accompanying CHP inspection truck inspection teams on depot inspections. The fully burdened cost for these inspectors was taken at $40,000 each, which is somewhat higher than ARB's current budgetary figures. Many of these inspectors would be posted at remote locations, which was assumed to increase their overhead rates. Average travel and per-diem expenses of $5,000 per inspector per year were also assumed.

Assuming that three hours of each inspector's day was spent on smoke observations (at two trucks per minute), two hours on issuing smoke citations (at ten minutes each), and three hours on anti-tampering inspections (at 15 minutes each), each inspector could smoke check 180 trucks per day, issue smoke citations to twelve of them, and conduct 9 anti-tampering inspections. This amounts to about 2.9 million smoke checks, 192,000 smoke citations, and 144,000 anti-tampering inspections per year; or about 11 smoke checks, 0.74 smoke citations, and 0.56 anti-tampering inspections for each heavy-duty diesel vehicle in California.

In addition, the smoke enforcement program was assumed to consume all of the time of 20 full-time smoke enforcement officers in the South Coast, Bay Area, and other critical air basins, and about 5 percent of the time of 500 traffic patrol officers in the CHP and various local jurisdictions.

4.3 Indirect Costs

It takes time to take a truck in for inspection, and even more time to have it fixed and reinspected if it fails. This time costs money, both for the capital charges on the vehicle itself and for the wages and benefits of the driver. For a medium-heavy or heavy-heavy truck, the daily capital charge is about $80, while the charge for a light-heavy duty truck is about half that, or $40. The fully-burdened rate for a driver with a Class 1 licence (required for a heavy-heavy and most medium-heavy trucks) is about $20 per hour. For a light-heavy duty truck we assumed the driver's cost was $15 per hour.

Allowing for inefficiencies and scheduling problems, about three day hours of truck and driver time would be required for a typical I/M inspection, resulting in a cost of $60 (for a light-heavy) to $90 (for a medium or heavy-heavy). Any required repairs would result in the vehicle being out of service for another full day, but would require only about two more hours of driver time. Transit buses were assumed to be tested on-site as part of their normal maintenance, so that they would not incur any time losses due to the inspection. Required repairs would result in lost time, however.

5.0 THE EFFECTS OF ALTERNATIVE I/M PROGRAMS: A SIMPLIFIED MODEL

An inspection and maintenance program reduces total motor-vehicle emissions by reducing the frequency of occurrence in the vehicle population of the kinds of defects which result in increased emissions. In order to estimate the impact of alternative I/M programs on overall emissions, it was necessary to estimate the impact of each type of program on the frequency of occurrence of the 18 types of emissions-related defects defined in Volume II. For consistency in making these estimates, Radian developed a simple model of the reduction in defect frequency due to different types of I/M programs.

5.1 Model Specification

An I/M program reduces the frequency of occurrence of emissions defects through several mechanisms. First, the very existence of an I/M program will act to deter many people from tampering with emissions controls. The program will also detect some of those cases of tampering which are not deterred, and require that they be repaired. The program may also detect malmaintenance-related defects which would not be fixed for some time--if at all--and require that they be fixed immediately. This reduces the average time that a vehicle operates with a given defect, and thus the overall frequency of occurrence of that type of defect in the vehicle fleet.

The simple model of I/M program effects developed for this study incorporates all of these mechanisms, by means of a set of exogenously specified parameters which are specific to each scenario and each type of defect. These parameters are the following:

- T Fraction of this type of defect which are due to tampering in the baseline (no I/M) case;
- D Fraction of tampering instances deterred by the I/M program;

C   Fraction of those tampering instances which are not deterred that are caught by the I/M inspection;

L   Average delay from the time a non-tampering defect occurs to the time it would be repaired in the absence of an I/M program, expressed as a fraction of a year;

N   Fraction of the non-tampering defects which would never be fixed in the absence of an I/M program;

Z   Fraction of non-tampering related defects detected by the I/M program;

W   Fraction of the non-tampering defects detected which are not repaired as a result of cost exceedance.

With these parameters specified, the fractional reduction in the frequency of occurrence of a given defect due to an annual I/M program is given by:

$$R = T \cdot (D + P_1 \cdot (1-D) \cdot C) + (1-T) \cdot Z \cdot (1-W) \cdot (P_2 \cdot L \cdot (1-N) + P_3 \cdot N) \qquad (5\text{-}1)$$

where P_1, P_2, and P_3 are numerical values which account for the fraction of time the vehicle operated with the defect before it was repaired, and the likelihood of its recurring. The frequency $F_{i/m}$ of defect occurrence with the I/M program is then obtained from the frequency F_o without I/M by

$$F_{i/m} = F_o \cdot (1 - R) \qquad (5\text{-}2)$$

The first term in Equation 5-1 accounts for the reduction in defects due to tampering. Defects which never occur due to the would-be tamperer having been deterred by the I/M program obviously contribute proportionally to reducing defect frequency. For defects which are caught and fixed by the program, the results are less obvious. If tampering were a completely random act, then each vehicle would operate with its defect, on average, for half a year before it was detected and corrected, and the appropriate value for P_1 would be 0.5. If all tamperers, once caught, were completely deterred, then long-term value of P_1 would be close to 1.0. If, on the other hand, all tamperers immediately tampered again after completing the I/M inspection, the value of P_1 would be nearly zero. For this study, P_1 was taken as equal to 0.5 for the annual inspection programs, and as 0.35 for the biennial programs.

The second term in Equation 5-1 reflects repairs to non-tampering related defects. Those non-tampering defects which are detected, and which do not receive a waiver due to cost exceedance, will be repaired. Some of those defects would not have been repaired except for the I/M program, while some would have been repaired in the future. The term involving P_2 accounts for the reduction in defect frequency due to repairing the problem now, rather than at some time L in the future. This reduction is equal to the fraction of a year that the vehicle would have operated with the defect in the absence of an I/M program. For an annual inspection program, the average value for this fraction is one-half of L, and the value of P_2 is 0.5. For a biennial program, P_2 has a value of 0.25.

The term in Equation 5-1 involving P_3 accounts for the reduction in emissions due to repairing defects which would not otherwise be repaired over the life of the vehicle. Most vehicles in this situation have only limited remaining life. We assumed that, on average, this remaining life would amount to about 2 years. This results in a value of 0.8 for P_3 for the annual inspection cases, and 0.6 for the biennial inspections.

For the in-use inspection scenarios, the "inspection frequency" is not well defined. For these cases, we defined an "effective inspection frequency", which differed for different types of defects. For visually obvious defects, such as heavy continuous smoke, the effective inspection frequency was taken as fairly high--up to twelve times per year. For defects that would only be detected in an underhood inspection, the effective inspection frequency was much lower, typically once per year. The parameters P_1, P_2, and P_3 were then defined as functions of the effective inspection frequency.

It should be noted that this simplified model of I/M effectiveness is applicable only for a "steady-state" program--i.e. only after the program has operated for long enough that all vehicles have been through it at least once. No attempt has been made to account for the "phase-in" effects during the first year or two.

Repair costs and probability--the model described above can also be used to estimate the average costs per vehicle for emissions-related repairs and corrections to tampering, as well as the probability that such repairs will be required. Assuming that a given defect costs Q dollars to repair, the average cost per vehicle Q_{avg} for non-tampering repairs due to that type of defect as a result of the I/M program is given by

$$Q_{avg} = Q \cdot (1-T) \cdot Z \cdot (1-W) \cdot (P_2 \cdot L \cdot (1-N)+N) \qquad (5-3)$$

The average costs per vehicle to repair tampering are given by

$$Q_{avg} = Q \cdot T \cdot (1-D) \cdot C \qquad (5-4)$$

The aggregate repair costs for all types of emission-related defects can be calculated by summing the values of Q_{avg} calculated for each defect.

The fraction of vehicles in the fleet requiring repairs for a given type of defect is given by

$$F = T \cdot (1-D) \cdot C + (1-T) \cdot Z \cdot (1-W) \cdot (P_2 \cdot L \cdot (1-N)+N) \qquad (5-5)$$

To calculate the aggregate fraction of vehicles requiring repairs due to all defects is more complicated, however. Since a vehicle may require repairs for more than one defect at a time, it is necessary to account for the overlap. If vehicles of a given class have a probability P_a of needing repairs due to defect A, and probability P_b of needing repairs for defect B, then the probability of needing repairs for defect A or B or both is given by

$$P_{ab} = P_a + P_b - P_a \cdot P_b \tag{5-6}$$

if defects A and B are independently distributed.

To calculate the fraction of vehicles requiring repairs, the different types of defects were first combined into groups of mutually exclusive defects. For example, retarded injection timing and advanced injection timing are mutually exclusive, so the repair frequencies for these defects can simply be added. The same is true for the different severities of fuel injection problems, catalytic converters and traps, and so forth.

The probability distributions for each such group were assumed to be independent of the distributions for all other groups, so that they could be combined by a recursive application of Equation 5-6. This assumption probably resulted in overestimating the number of vehicles requiring repairs, since the probability of requiring different sorts of repairs is not really independently distributed. As is well known, a poorly maintained vehicle is much more likely to require repairs of all sorts than a well-maintained vehicle.

The values of Q used in Equations 5-4 and 5-5 were taken from Table 3-5. These values were modified, however, to reflect the effects of repair cost limits where these were applicable. In some cases, a vehicle owner might decide to repair a defect, even though the cost would exceed the cost limit. In this case, it would be inappropriate to allocate the full cost of the repair to the I/M program, since the repair obviously had some value to the owner over and above the repair cost limit. Thus, the maximum repair cost allocated to the program for any one defect was limited to no more than the repair cost limit for the given scenario.

Fines for tampering--In the Case 2 and Case 2a scenarios, vehicle owners were assumed to be subject to a substantial fine if they were caught operating a tampered vehicle. The fraction of vehicles in which tampering is detected is given by

$$F = T \cdot (1-D) \cdot C \qquad (5\text{-}7)$$

Tampering would not necessarily be provable in all of the cases in which it was detected, however. In addition, there would be some tendency to issue warnings, nominal fines, etc. to first offenders and perceived "special" cases. This would reduce the fraction of the vehicle owners caught tampering who were actually fined. For this study, we assumed that 50% of the detected cases of tampering would result in fines.

Offensive smoke--One objective of this project was to quantify the effects of alternative I/M programs on occurrences of offensive visible smoke. This proved very difficult to do, and only a rough solution was possible. This rough solution involves the definition of an offensive smoke index, which is a dimensionless value which can be considered to be related to the frequency of occurrence of offensively smoky trucks and buses in the population. As a rough guide, a truck would be considered to be offensively smoky if it had an acceleration smoke opacity of 40 percent or more, or a steady-state smoke opacity exceeding about 15 percent. For buses, the criteria for offensiveness would be about 20 percent and 8 percent, respectively.

To calculate the offensive smoke index for the vehicle fleet, we assigned visible smoke indices ranging from zero to 1.0 to each type of emissions-related defect. Low indices were assigned to those defects having little or no effect on visible smoke, while high indices were assigned to defects (such as severe injection problems and disabled puff limiters) which result in very high smoke emissions. The offensive smoke index for a given vehicle class was then obtained by multiplying the smoke index for each defect by the frequency of occurrence of that defect in that class, and then summing over all defects. This formula was suitable for model years up to 1990. For 1991 and later years the calculation was modified to reflect the effects of trap-oxidizers. A vehicle with a functioning trap was assumed to be unable to emit offensive levels of smoke except when operating in the bypass mode, which was assumed to occur 10 percent of the time.

5.2 I/M Program Scenarios

In order to estimate the effects of the different I/M program scenarios in a consistent way, we prepared a different set of I/M model parameters for each scenario, varying the parameter values assumed in order to reflect the scenario characteristics. The input assumptions for each scenario, as well as the resulting reductions in defect frequency, are shown in Tables 5-1 through 5-9. The remainder of this section discusses the assumptions and considerations which entered into each of these sets of model inputs.

The reader is cautioned not to rely overmuch on the specific values shown in these tables, or in the tables of model results which presented in the following sections. Due to the absence of actual data on I/M program effectiveness for heavy-duty diesels, the inputs and outputs shown contain considerable uncertainty, and their precise numerical accuracy should not be relied on.

This should not be taken as implying that the results presented here are useless as a guide to policy, however. Because the assumptions and approaches used <u>are</u> consistent from scenario to scenario, we have considerable confidence in the model's indications of the relative effectiveness of different I/M approaches, even though the absolute numbers calculated include much uncertainty. These data should be understood and interpreted in this light.

TABLE 5-1. I/M EFFECTS MODEL INPUTS FOR CASE 1: ANNUAL DECENTRALIZED I/M INSPECTION

Defect Type	Percent Due to Tampering	Tampering: Pcnt. Deterred	Tampering: Pcnt. Detected	Maintenance: Pcnt.Ann. Mi.to Fix	Maintenance: Pcnt. Not Fixed	Maintenance: Pcnt. Detected	Maintenance: Pcnt. Waived	Net Reduction
Timing Advanced	66%	50%	80%	200%	50%	80%	5%	69%
Timing Retarded	0%	0%	0%	200%	30%	45%	5%	40%
Minor Inj. Problems	0%	0%	0%	100%	50%	45%	20%	23%
Mod. Inj. Problems	0%	0%	0%	30%	20%	75%	5%	20%
Severe Inj. Problems	0%	0%	0%	5%	10%	95%	2%	10%
Puff Lt'er Misset	70%	50%	60%	100%	50%	75%	10%	59%
Puff Lt'er Disabled	90%	50%	70%	100%	50%	85%	3%	66%
Maximum Fuel High	90%	50%	70%	100%	20%	45%	5%	63%
Clogged Air Filter	0%	0%	0%	20%	10%	75%	1%	13%
Wrong/Worn Turbo	30%	60%	50%	50%	20%	50%	20%	31%
Intercooler Clogged	0%	0%	0%	50%	20%	65%	20%	19%
Other Air Problems	0%	0%	0%	50%	20%	50%	10%	16%
Engine Mech. Failure	0%	0%	0%	5%	20%	98%	80%	4%
Excess Oil Cons.	0%	0%	0%	30%	20%	95%	70%	8%
Electronics Failed	0%	0%	0%	10%	10%	65%	5%	8%
Electronics Tampered	100%	50%	50%			0%		63%
Catalyst Removed	90%	70%	60%	100%	80%	95%	20%	77%
Trap Removed/Bypassed	80%	50%	40%	100%	80%	90%	20%	59%
EGR Disabled	80%	40%	40%	100%	80%	85%	2%	54%

TABLE 5-2. I/M EFFECTS MODEL INPUTS FOR CASE 1a: CENTRALIZED I/M INSPECTION

		Tampering		Maintenance				
Defect Type	Percent Due to Tampering	Pcnt. Deterred	Pcnt. Detected	Pcnt.Ann. Mi.to Fix	Pcnt. Not Fixed	Pcnt. Detected	Pcnt. Waived	Net Reduction
Timing Advanced	66%	60%	90%	200%	50%	90%	5%	78%
Timing Retarded	0%	0%	0%	200%	30%	50%	5%	45%
Minor Inj. Problems	0%	0%	0%	100%	50%	40%	20%	21%
Mod. Inj. Problems	0%	0%	0%	30%	20%	70%	5%	19%
Severe Inj. Problems	0%	0%	0%	5%	10%	100%	2%	10%
Puff Lt'er Misset	70%	60%	80%	100%	50%	80%	10%	67%
Puff Lt'er Disabled	90%	60%	80%	100%	50%	100%	3%	75%
Maximum Fuel High	90%	60%	80%	100%	20%	50%	5%	71%
Clogged Air Filter	0%	0%	0%	20%	10%	80%	1%	13%
Wrong/Worn Turbo	30%	80%	60%	50%	20%	60%	20%	38%
Intercooler Clogged	0%	0%	0%	50%	20%	70%	20%	20%
Other Air Problems	0%	0%	0%	50%	20%	60%	10%	19%
Engine Mech. Failure	0%	0%	0%	5%	20%	100%	80%	4%
Excess Oil Cons.	0%	0%	0%	30%	20%	100%	70%	8%
Electronics Failed	0%	0%	0%	10%	10%	70%	5%	8%
Electronics Tampered	100%	70%	60%	100%	80%	0%	20%	79%
Catalyst Removed	90%	80%	70%	100%	80%	100%	20%	84%
Trap Removed/Bypassed	80%	60%	50%	100%	80%	100%	20%	68%
EGR Disabled	80%	50%	50%	100%	80%	90%	2%	63%

TABLE 5-3. I/M EFFECTS MODEL INPUTS FOR CASE 1b: $500 COST LIMIT

Defect Type	Percent Due to Tampering	Tampering: Pcnt. Deterred	Tampering: Pcnt. Detected	Maintenance: Pcnt. Ann. Mi. to Fix	Maintenance: Pcnt. Not Fixed	Maintenance: Pcnt. Detected	Maintenance: Pcnt. Waived	Net Reduction
Timing Advanced	66%	50%	80%	200%	50%	80%	10%	68%
Timing Retarded	0%	0%	0%	200%	30%	45%	10%	38%
Minor Inj. Problems	0%	0%	0%	100%	50%	45%	40%	18%
Mod. Inj. Problems	0%	0%	0%	30%	20%	75%	20%	17%
Severe Inj. Problems	0%	0%	0%	5%	10%	95%	5%	9%
Puff Lt'er Misset	70%	50%	60%	100%	50%	75%	20%	57%
Puff Lt'er Disabled	90%	50%	70%	100%	50%	85%	10%	66%
Maximum Fuel High	90%	50%	70%	100%	20%	45%	20%	63%
Clogged Air Filter	0%	0%	0%	20%	10%	75%	5%	12%
Wrong/Worn Turbo	30%	60%	50%	50%	20%	50%	30%	30%
Intercooler Clogged	0%	0%	0%	50%	20%	65%	30%	16%
Other Air Problems	0%	0%	0%	50%	20%	50%	30%	13%
Engine Mech. Failure	0%	0%	0%	5%	20%	98%	90%	2%
Excess Oil Cons.	0%	0%	0%	30%	20%	95%	85%	4%
Electronics Failed	0%	0%	0%	10%	10%	65%	20%	7%
Electronics Tampered	100%	50%	50%	100%	80%	0%	20%	63%
Catalyst Removed	90%	70%	60%	100%	80%	95%	40%	75%
Trap Removed/Bypassed	80%	50%	40%	100%	80%	90%	40%	56%
EGR Disabled	80%	40%	40%	100%	80%	85%	5%	54%

TABLE 5-4. I/M EFFECTS MODEL INPUTS FOR CASE 1c: NO COST LIMIT FOR REPAIRS

Defect Type	Percent Due to Tampering	Tampering		Maintenance				Net Reduction
		Pcnt. Deterred	Pcnt. Detected	Pcnt.Ann. Mi.to Fix	Pcnt. Not Fixed	Pcnt. Detected	Pcnt. Waived	
Timing Advanced	66%	50%	80%	200%	50%	80%	0%	71%
Timing Retarded	0%	0%	0%	200%	30%	45%	0%	42%
Minor Inj. Problems	0%	0%	0%	100%	50%	45%	0%	29%
Mod. Inj. Problems	0%	0%	0%	30%	20%	75%	0%	21%
Severe Inj. Problems	0%	0%	0%	5%	10%	95%	0%	10%
Puff Lt'er Misset	70%	50%	60%	100%	50%	75%	0%	60%
Puff Lt'er Disabled	90%	50%	70%	100%	50%	85%	0%	66%
Maximum Fuel High	90%	50%	70%	100%	20%	45%	0%	63%
Clogged Air Filter	0%	0%	0%	20%	10%	75%	0%	13%
Wrong/Worn Turbo	30%	60%	50%	50%	20%	50%	0%	34%
Intercooler Clogged	0%	0%	0%	50%	20%	65%	0%	23%
Other Air Problems	0%	0%	0%	50%	20%	50%	0%	18%
Engine Mech. Failure	0%	0%	0%	5%	20%	98%	0%	18%
Excess Oil Cons.	0%	0%	0%	30%	20%	95%	0%	27%
Electronics Failed	0%	0%	0%	10%	10%	65%	0%	8%
Electronics Tampered	100%	50%	50%	100%	80%	0%	0%	63%
Catalyst Removed	90%	70%	60%	100%	80%	95%	0%	78%
Trap Removed/Bypassed	80%	50%	40%	100%	80%	90%	0%	61%
EGR Disabled	80%	40%	40%	100%	80%	85%	0%	54%

TABLE 5-5. I/M EFFECTS MODEL INPUTS FOR CASE 1d: NO GASEOUS EMISSIONS MEASUREMENT

		Tampering		Maintenance				
Defect Type	Percent Due to Tampering	Pcnt. Deterred	Pcnt. Detected	Pcnt.Ann. Mi.to Fix	Pcnt. Not Fixed	Pcnt. Detected	Pcnt. Waived	Net Reduction
Timing Advanced	66%	30%	50%	200%	50%	0%	5%	31%
Timing Retarded	0%	0%	0%	200%	30%	30%	5%	27%
Minor Inj. Problems	0%	0%	0%	100%	50%	30%	20%	16%
Mod. Inj. Problems	0%	0%	0%	30%	20%	60%	5%	16%
Severe Inj. Problems	0%	0%	0%	5%	10%	90%	2%	9%
Puff Lt'er Misset	70%	50%	60%	100%	50%	75%	10%	59%
Puff Lt'er Disabled	90%	50%	70%	100%	50%	85%	3%	66%
Maximum Fuel High	90%	50%	70%	100%	20%	45%	5%	63%
Clogged Air Filter	0%	0%	0%	20%	10%	75%	1%	13%
Wrong/Worn Turbo	30%	60%	50%	50%	20%	50%	20%	31%
Intercooler Clogged	0%	0%	0%	50%	20%	40%	20%	12%
Other Air Problems	0%	0%	0%	50%	20%	50%	10%	16%
Engine Mech. Failure	0%	0%	0%	5%	20%	80%	80%	3%
Excess Oil Cons.	0%	0%	0%	30%	20%	40%	70%	3%
Electronics Failed	0%	0%	0%	10%	10%	60%	5%	7%
Electronics Tampered	100%	40%	30%	100%	80%	0%	20%	49%
Catalyst Removed	90%	60%	20%	100%	80%	5%	20%	58%
Trap Removed/Bypassed	80%	50%	40%	100%	80%	90%	20%	59%
EGR Disabled	80%	40%	30%	100%	80%	20%	2%	42%

TABLE 5-6. I/M EFFECTS MODEL INPUTS FOR CASE 1e: BIENNIAL INSPECTION

Defect Type	Percent Due to Tampering	Tampering: Pcnt. Deterred	Tampering: Pcnt. Detected	Maintenance: Pcnt.Ann. Mi.to Fix	Maintenance: Pcnt. Not Fixed	Maintenance: Pcnt. Detected	Maintenance: Pcnt. Waived	Net Reduction
Timing Advanced	66%	30%	80%	200%	50%	80%	5%	62%
Timing Retarded	0%	0%	0%	200%	30%	45%	5%	40%
Minor Inj. Problems	0%	0%	0%	100%	50%	45%	20%	23%
Mod. Inj. Problems	0%	0%	0%	30%	20%	75%	5%	20%
Severe Inj. Problems	0%	0%	0%	5%	10%	95%	2%	10%
Puff Lt'er Misset	70%	30%	60%	100%	50%	75%	10%	49%
Puff Lt'er Disabled	90%	30%	70%	100%	50%	85%	3%	54%
Maximum Fuel High	90%	30%	70%	100%	20%	45%	5%	51%
Clogged Air Filter	0%	0%	0%	20%	10%	75%	1%	13%
Wrong/Worn Turbo	30%	40%	50%	50%	20%	50%	20%	27%
Intercooler Clogged	0%	0%	0%	50%	20%	65%	20%	19%
Other Air Problems	0%	0%	0%	50%	20%	50%	10%	16%
Engine Mech. Failure	0%	0%	0%	5%	20%	98%	80%	4%
Excess Oil Cons.	0%	0%	0%	30%	20%	95%	70%	8%
Electronics Failed	0%	0%	0%	10%	10%	65%	5%	8%
Electronics Tampered	100%	30%	50%	100%	80%	0%	20%	48%
Catalyst Removed	90%	50%	60%	100%	80%	95%	20%	64%
Trap Removed/Bypassed	80%	30%	40%	100%	80%	90%	20%	46%
EGR Disabled	80%	20%	40%	100%	80%	85%	2%	41%

TABLE 5-7. I/M EFFECTS MODEL INPUTS FOR CASE 1f: CURRENT SMOG CHECK LAW

Defect Type	Percent Due to Tampering	Tampering Pcnt. Deterred	Tampering Pcnt. Detected	Maintenance Pcnt.Ann. Mi.to Fix	Maintenance Pcnt. Not Fixed	Maintenance Pcnt. Detected	Maintenance Pcnt. Waived	Net Reduction
Timing Advanced	66%	30%	70%	200%	50%	80%	80%	41%
Timing Retarded	0%	0%	0%	200%	30%	40%	80%	8%
Minor Inj. Problems	0%	0%	0%	100%	50%	40%	95%	1%
Mod. Inj. Problems	0%	0%	0%	30%	20%	70%	80%	4%
Severe Inj. Problems	0%	0%	0%	5%	10%	90%	70%	3%
Puff Lt'er Misset	70%	30%	50%	100%	50%	70%	60%	39%
Puff Lt'er Disabled	90%	30%	60%	100%	50%	80%	80%	47%
Maximum Fuel High	90%	30%	50%	100%	20%	40%	80%	43%
Clogged Air Filter	0%	0%	0%	20%	10%	70%	50%	6%
Wrong/Worn Turbo	30%	40%	30%	50%	20%	50%	90%	16%
Intercooler Clogged	0%	0%	0%	50%	20%	60%	90%	2%
Other Air Problems	0%	0%	0%	50%	20%	50%	60%	7%
Engine Mech. Failure	0%	0%	0%	5%	20%	95%	90%	2%
Excess Oil Cons.	0%	0%	0%	30%	20%	90%	95%	1%
Electronics Failed	0%	0%	0%	10%	10%	50%	60%	3%
Electronics Tampered	100%	30%	30%	100%	80%	0%	20%	41%
Catalyst Removed	90%	50%	50%	100%	80%	60%	100%	56%
Trap Removed/Bypassed	80%	30%	20%	100%	80%	60%	100%	30%
EGR Disabled	80%	20%	30%	100%	80%	60%	50%	30%

TABLE 5-8. I/M EFFECTS MODEL INPUTS FOR CASE 2: IN-USE INSPECTION/$1000 COST LIMIT

			Tampering		Maintenance				
Defect Type	Equiv. Insp. Freq./Yr.	Percent Due to Tampering	Pcnt. Deterred	Pcnt. Detected	Pcnt. Ann. Mi.to Fix	Pcnt. Not Fixed	Pcnt. Detected	Pcnt. Waived	Net Reduction
Timing Advanced	1	66%	30%	20%	200%	50%	0%	5%	24%
Timing Retarded	6	0%			200%	30%	20%	5%	18%
Minor Inj. Problems	6	0%			100%	50%	30%	20%	22%
Mod. Inj. Problems	6	0%			30%	20%	70%	5%	49%
Severe Inj. Problems	12	0%			5%	10%	95%	2%	36%
Puff Lt'er Misset	6	70%	50%	70%	100%	50%	60%	10%	73%
Puff Lt'er Disabled	6	90%	80%	95%	100%	50%	95%	3%	96%
Maximum Fuel High	6	90%	40%	20%	100%	20%	20%	5%	48%
Clogged Air Filter	6	0%			20%	10%	60%	1%	36%
Wrong/Worn Turbo	6	30%	30%	20%	50%	20%	30%	20%	27%
Intercooler Clogged	6	0%			50%	20%	30%	20%	20%
Other Air Problems	6	0%			50%	20%	30%	10%	22%
Engine Mech. Failure	12	0%			5%	20%	80%	80%	7%
Excess Oil Cons.	12	0%			30%	20%	50%	70%	13%
Electronics Failed	1	0%			10%	10%	20%	5%	2%
Electronics Tampered	1	100%	60%	40%	200%		0%	20%	68%
Catalyst Removed	1	90%	80%	70%	100%	80%	50%	20%	81%
Trap Removed/Bypassed	6	80%	80%	90%	100%	80%	90%	20%	91%
EGR Disabled	1	80%	60%	80%	100%	80%	70%	2%	71%

TABLE 5-9. I/M EFFECTS MODEL INPUTS FOR CASE 2a: IN-USE INSPECTION WITH NO COST LIMIT

			Tampering		Maintenance				
Defect Type	Equiv. Insp. Freq./Yr.	Percent Due to Tampering	Pcnt. Deterred	Pcnt. Detected	Pcnt. Ann. Mi. to Fix	Pcnt. Not Fixed	Pcnt. Detected	Pcnt. Waived	Net Reduction
Timing Advanced	1	66%	30%	20%	200%	50%	0%	0%	24%
Timing Retarded	6	0%			200%	30%	20%	0%	19%
Minor Inj. Problems	6	0%			100%	50%	30%	0%	28%
Mod. Inj. Problems	6	0%			30%	20%	70%	0%	52%
Severe Inj. Problems	12	0%			5%	10%	95%	0%	36%
Puff Lt'er Misset	6	70%	50%	70%	100%	50%	60%	0%	74%
Puff Lt'er Disabled	6	90%	80%	95%	100%	50%	95%	0%	96%
Maximum Fuel High	6	90%	40%	20%	100%	20%	20%	0%	48%
Clogged Air Filter	6	0%			20%	10%	60%	0%	36%
Wrong/Worn Turbo	6	30%	30%	20%	50%	20%	30%	0%	30%
Intercooler Clogged	6	0%			50%	20%	30%	0%	25%
Other Air Problems	6	0%			50%	20%	30%	0%	25%
Engine Mech. Failure	12	0%			5%	20%	80%	0%	36%
Excess Oil Cons.	12	0%			30%	20%	50%	0%	43%
Electronics Failed	1	0%			10%	10%	20%	0%	2%
Electronics Tampered	1	100%	60%	40%	200%		0%	0%	68%
Catalyst Removed	1	90%	80%	70%	100%	80%	50%	0%	82%
Trap Removed/Bypassed	6	80%	80%	90%	100%	80%	90%	0%	94%
EGR Disabled	1	80%	60%	80%	100%	80%	70%	0%	71%

Case 1--This scenario is intended to reflect the results of an effective and vigorously enforced periodic I/M program. We assumed that the presence of the I/M program would deter most tampering with emissions controls. However, much of the tampering which would occur under this scenario was assumed to be done "reversibly", so that it could be put right before taking the vehicle in for inspection. The rate of detection of tampering was thus assumed to be rather low. Detection rates for most maintenance-related items were assumed to be fairly high, reflecting the effectiveness of the combined smoke and gaseous emissions measurements. Waiver rates were set fairly low, to reflect the $1,000 cost limit in this scenario.

Case 1a--This scenario is similar to Case 1, but reflects the more effective inspection possible in a centralized I/M program. This results in greater tampering deterrence and higher detection rates than for the decentralized case.

Case 1b--This scenario is identical to Case 1, except for the lower repair cost limit, which resulted in higher waiver rates.

Case 1c--This scenario is also identical to Case 1, except for the zero waiver rate, reflecting the absence of a repair cost limit.

Case 1d--This scenario is similar to Case 1, but reflects the effects of omitting the gaseous emissions measurements. This results in lower rates of defect detection and tampering deterrence, especially for those defects which would increase HC or NO_x emissions, but not visible smoke.

Case 1e--This scenario is similar to Case 1, but involves a biennial inspection rather than an annual one. The longer period between inspections was assumed to reduce tampering deterrence somewhat, as well as reducing the impact of required repairs on the overall defect frequency.

Case 1f--This scenario reflects the application of the current Smog Check law, including the $100 repair cost limit. This results in waiver rates of nearly 100 percent for most types of defects. The rates do not actually reach 100 percent, since some vehicle owners will choose to repair a defect even if the cost exceeds the cost limit. This scenario is otherwise similar to Case 1e.

Case 2--This scenario reflects the assumed results of a vigorous in-use smoke enforcement and anti-tampering inspection program. The tampering deterrence and detection rates for this program were assumed to be fairly high, since inspections would be frequent and unpredictable, and since provable tampering would result in a large fine. Detection rates for smoke-related maintenance problems were also taken to be fairly high, although not as high as for the dynamometer tests. This was offset by the greater frequency of inspection, resulting in a much greater probability of detecting and correcting a defect before it would be repaired in any case. Detection rates for non smoke-related defects were estimated to be fairly low. The waiver rates for this scenario were assumed to be similar to those for Case 1, reflecting the similar cost limits.

Case 2a--This scenario is identical to Case 1, except that the waiver rate is taken as zero, reflecting the absence of a repair cost limit.

6.0 MODEL RESULTS: REDUCTION IN EMISSIONS

The I/M effects model described in Section Five was combined with the estimated frequency of occurrence of emissions-related defects for the baseline (no I/M) case to produce a modified set of frequency of occurrence estimates. The derivation of the baseline frequency of occurrence estimates is described in Volume II. These modified frequency estimates were used as input to the model of heavy-duty diesel emissions and fuel consumption which is also described in Volume II. This resulted in a new set of projections of total and excess heavy-duty diesel emissions for each of the nine I/M scenarios considered. Figures 6-1 through 6-5 summarize the results of these calculations for the three years 1990, 1995, and 2000. The year-by-year results of these model runs are given in the Appendix.

Figure 6-1 compares the projected emissions under each of the I/M scenarios considered in this report with the emissions for the baseline (no I/M) case for the year 1990. Figures 6-2 and 6-3 perform similar comparisons for the years 1995 and 2000. Figures 6-4 and 6-5 provide more detail on the reductions in excess emissions under each scenario. Figure 6-4 shows the emissions reduction for each pollutant (in tons/day, statewide) in 1990, 1995, and 2000, while Figure 6-5 shows the percentage reduction in excess emissions of each pollutant for the same years.

Several features of the data presented in these figures are worthy of note. First, excess NO_x emissions (while large in absolute terms) are still a fairly small fraction of total diesel NO_x. Thus, although some programs can significantly reduce excess NO_x emissions, this effect is small in proportion to overall NO_x emissions from heavy-duty diesels. This is not the case with HC or PM emissions. Since excess emissions of these pollutants account for a large fraction of total heavy-duty diesel emissions, an I/M program which significantly reduces these excess emissions can have a marked effect on the overall total.

NOx
Hydrocarbons
Particulate

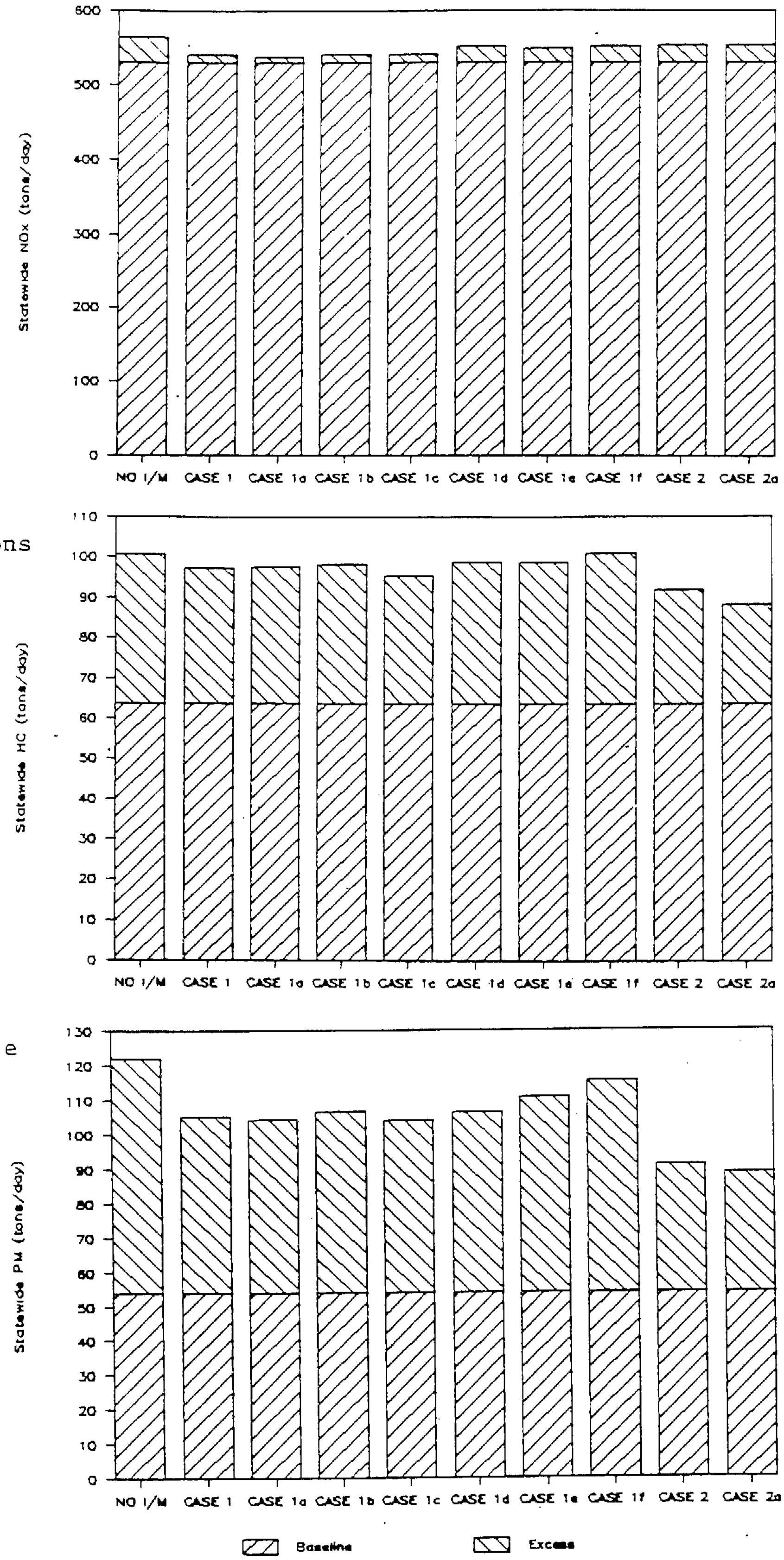


Figure 6-1. Comparison of I/M Scenarios: Total Emissions - 1990

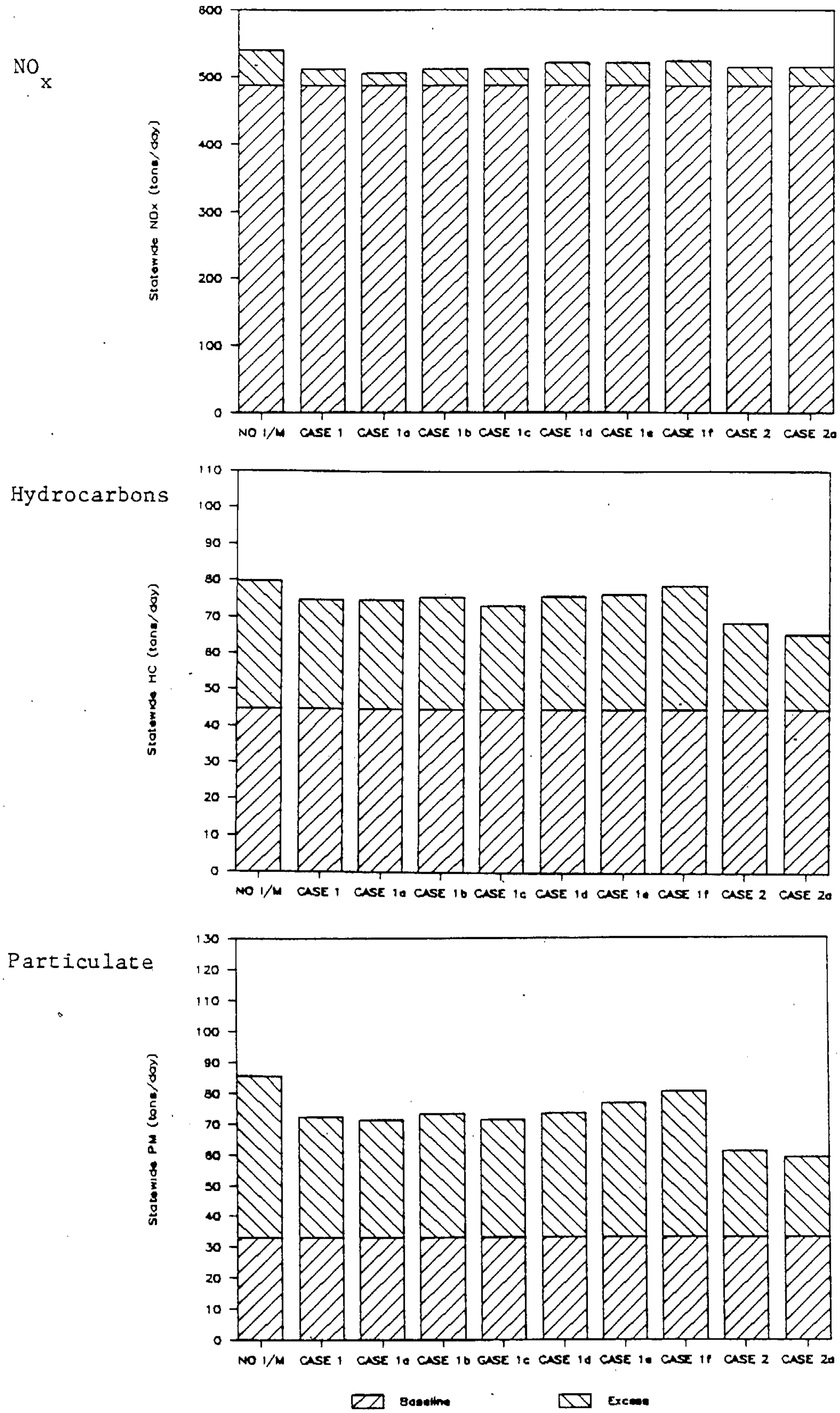


Figure 6-2. Comparison of I/M Scenarios: Total Emissions - 1995

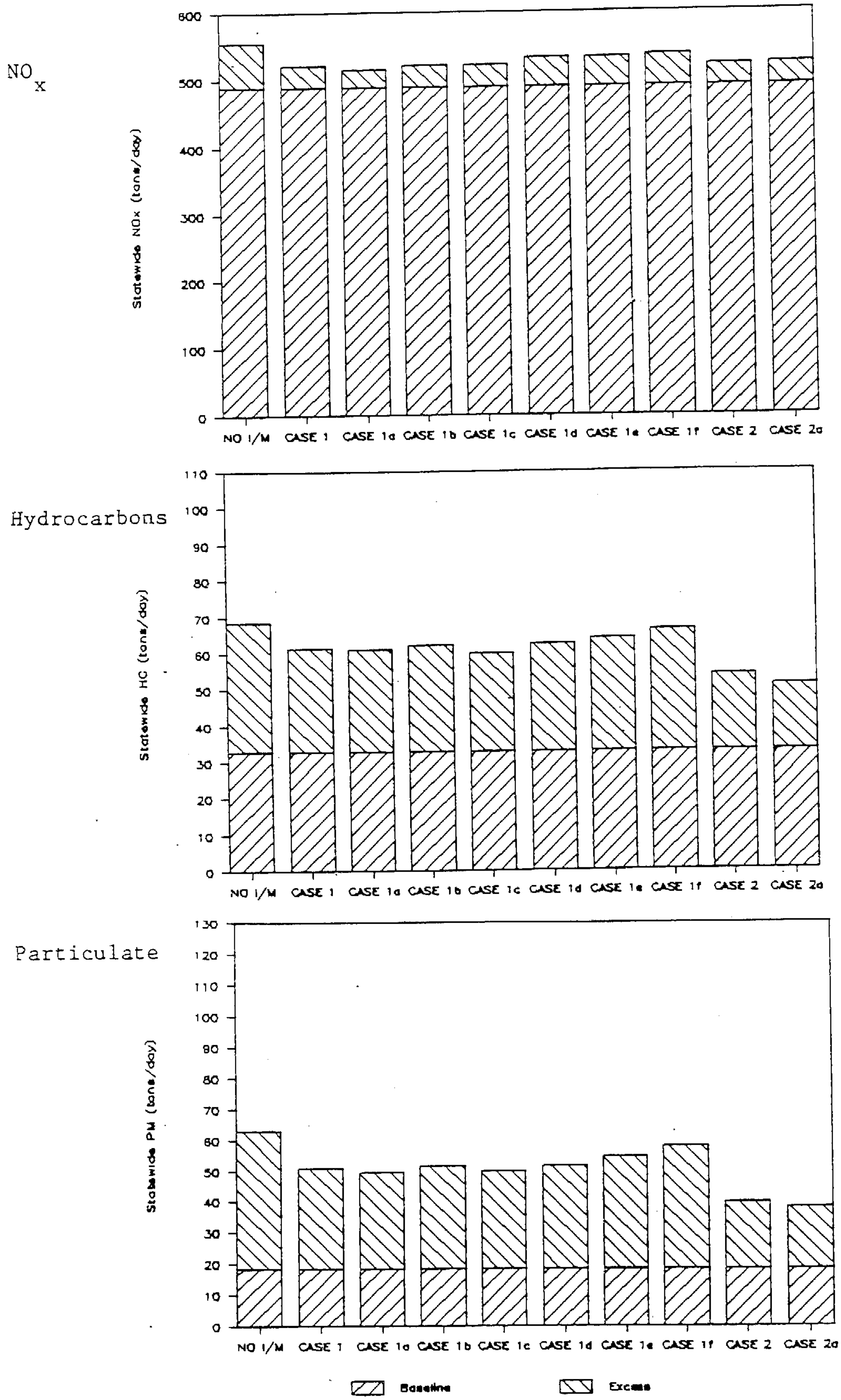


Figure 6-3. Comparison of I/M Scenarios: Total Emissions - 2000

1990

1995

2000

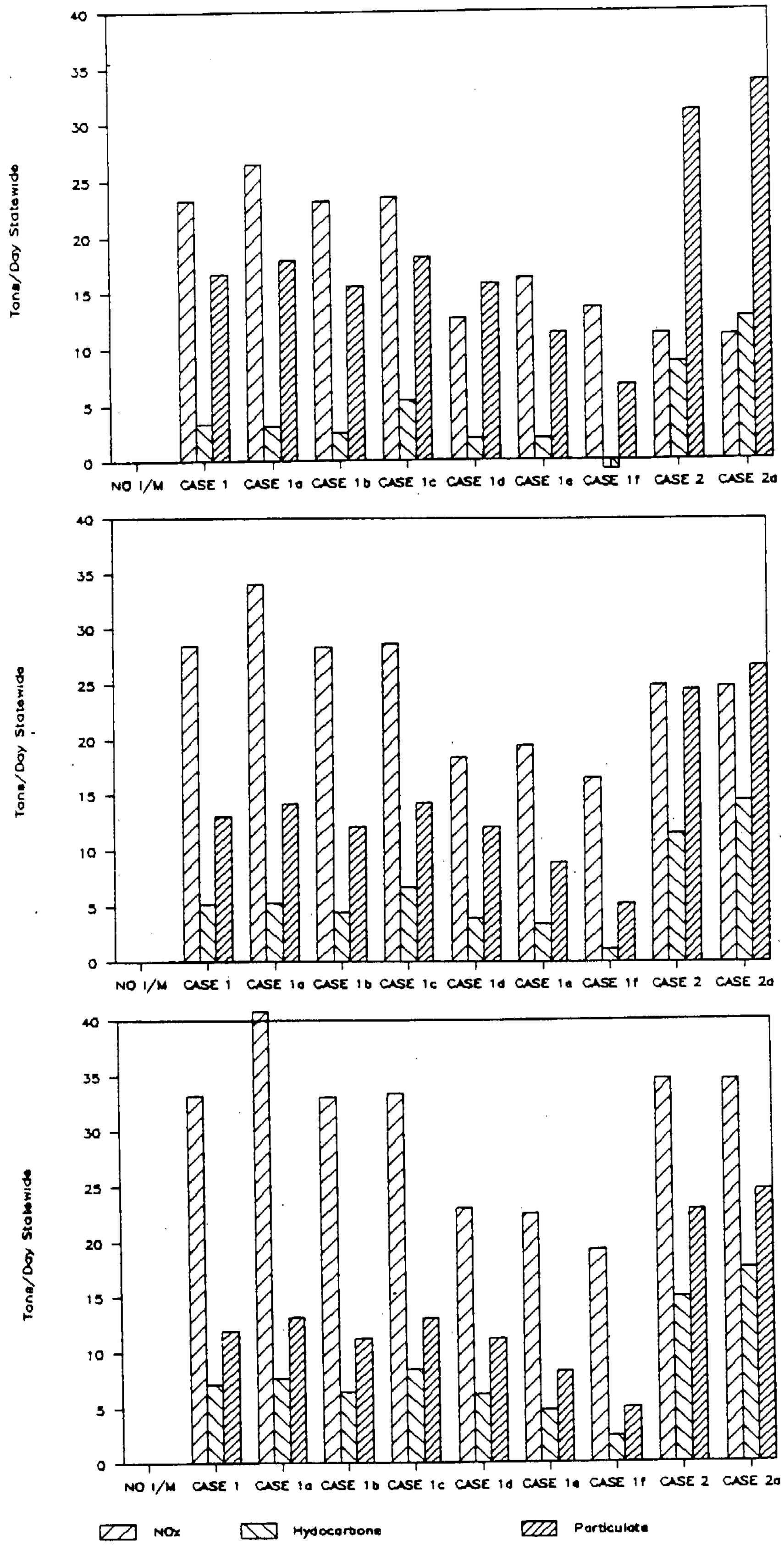


Figure 6-4. Comparison of I/M Scenarios: Reduction in Emissions Due to I/M

RADIAN
CORPORATION

1990

1995

2000

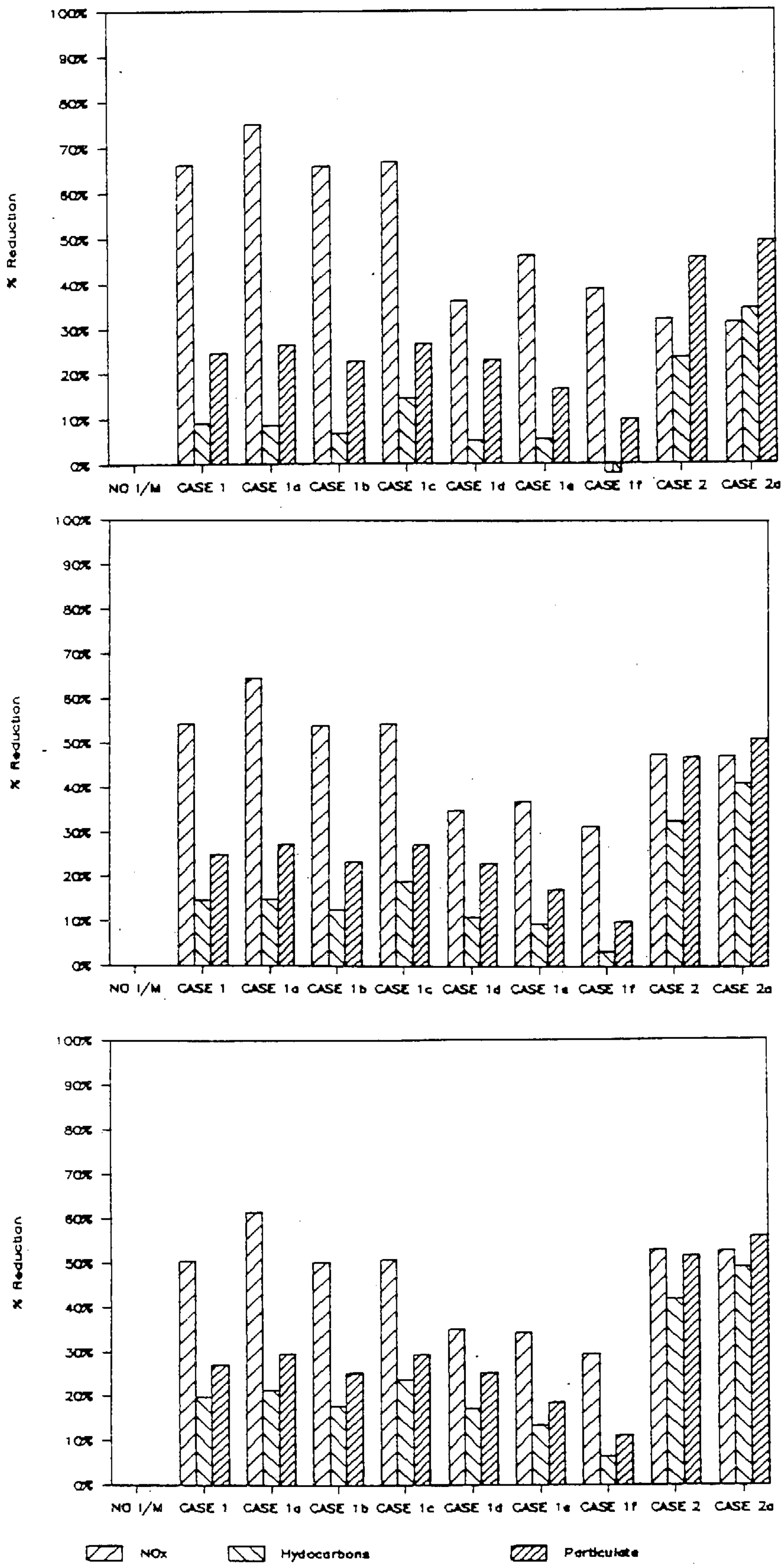


Figure 6-5. Comparison of I/M Scenarios: Percent Reduction in Excess Emissions Due to I/M

As Figure 6-4 indicates, all of the annual inspection programs are reasonably effective in reducing excess NO_x, but they are less effective in reducing HC and PM emissions. The centralized program in Case 1a is marginally more effective in this regard, reflecting the greater probability of deterring or detecting tampering with the central inspection. All of these programs are hampered, however, by their relatively infrequent and predictable inspections, which limit the deterrence of "reversible" tampering, and which do relatively little to reduce the overall incidence of non-tampered high-emitting vehicles. The in-use inspection programs, on the other hand, are highly effective in reducing particulate and HC emissions--resulting in more than a 50 percent reduction in excess PM. These programs are less effective in reducing NO_x, however, especially in the earlier years of the program.

7.0 MODEL RESULTS: REPAIR COSTS, REPAIR PROBABILITY, AND OFFENSIVE SMOKE

As discussed in Section Five, the model of I/M program effects developed for this report was able to calculate, as a by-product of the frequency of occurrence of specific defects, the average cost per vehicle for repairs required by the I/M program, and for the correction of tampering. In addition, this model estimated the fraction of vehicles requiring I/M repairs, the offensive smoke index, and (for Cases 2 and 2a) the fraction of vehicles fined for tampering.

The average costs per vehicle for repairs and for correcting tampering enter into the calculation of overall program costs. So, too, does the fraction of the vehicle fleet requiring repairs, since this will affect both the number of re-inspections and the indirect cost of lost time for repairs. The data on the offensive smoke index are used in the next section to calculate the percentage reduction in offensive smoke due to the I/M program. Finally, the fraction of the vehicle fleet which is fined for tampering will clearly affect the costs to the truck owner and the revenues to the Government as a result of the program.

These values were calculated separately for vehicles in each of the 11 vehicle classes considered, for each of four groups of model years (corresponding to different emissions control technologies). The results of these calculations are shown in Tables 7-1 through 7-9. For the periodic inspection scenarios, the values shown reflect the results of a single (annual or biennial) inspection--thus, for the biennial inspection cases, the average costs per year would be only half of the values shown. For the in-use inspection scenarios, the values reflect the results of operating for one year while subject to the program, and the values shown are thus annual costs.

Several points concerning these tables are worth noting. First, as these tables show, the average cost of I/M repairs per vehicle varies considerably from one scenario to another, but is always quite low compared to the

TABLE 7-1. I/M EFFECTIVENESS MODEL RESULTS FOR CASE 1: ANNUAL DECENTRALIZED I/M INSPECTION

	Average Cost Per Vehicle For I/M Repairs				Average Cost Per Vehicle To Correct Tampering				Offensive Smoke Index				Probability of Requiring Repairs			
Vehicle Class	1966 -1987	1988 -1990	1991 -1993	1994 -2000	1966 -1987	1988 -1990	1991 -1993	1994 -2000	1966 -1987	1988 -1990	1991 -1993	1994 -2000	1966 -1987	1988 -1990	1991 -1993	1994 -2000
<u>Heavy-Heavy</u>																
Cal. Reg./Cal. Eng.	$86	$80	$64	$73	$71	$63	$36	$55	0.28	0.24	0.13	0.07	49%	44%	23%	29%
Cal. Reg./Fed. Eng.	$78	$69	$49	$74	$66	$69	$42	$68	0.26	0.22	0.11	0.06	46%	41%	24%	31%
Out of State Reg.	$0	$0	$0	$0	$0	$0	$0	$0	0.47	0.39	0.14	0.07	0%	0%	0%	0%
<u>Medium-Heavy</u>																
Cal. Reg./Cal. Eng.	$76	$71	$64	$74	$44	$38	$36	$43	0.23	0.21	0.13	0.08	38%	34%	25%	27%
Cal. Reg./Fed. Eng.	$74	$69	$64	$74	$42	$37	$36	$43	0.23	0.21	0.13	0.08	36%	33%	25%	27%
Out of State Reg.	$0	$0	$0	$0	$0	$0	$0	$0	0.38	0.33	0.18	0.10	0%	0%	0%	0%
<u>Light-Heavy</u>																
Cal. Reg./Cal. Eng.	$43	$46	$61	$56	$13	$16	$30	$32	0.17	0.18	0.12	0.09	28%	28%	28%	29%
Cal. Reg./Fed. Eng.	$43	$45	$61	$56	$13	$16	$30	$32	0.17	0.18	0.12	0.09	28%	28%	28%	29%
Out of State Reg.	$0	$0	$0	$0	$0	$0	$0	$0	0.21	0.23	0.16	0.11	0%	0%	0%	0%
<u>Transit Bus</u>																
Cal. Reg./Cal. Eng.	$59	$35	$33	$33	$19	$7	$8	$8	0.12	0.08	0.03	0.03	27%	13%	11%	11%
Cal. Reg./Fed. Eng.	$61	$35	$33	$33	$16	$6	$8	$8	0.12	0.08	0.03	0.03	27%	13%	11%	11%

TABLE 7-2. I/M EFFECTIVENESS MODEL RESULTS FOR CASE 1a: CENTRALIZED I/M INSPECTION

	Average Cost Per Vehicle For I/M Repairs				Average Cost Per Vehicle To Correct Tampering				Offensive Smoke Index				Probability of Requiring Repairs			
Vehicle Class	1966 -1987	1988 -1990	1991 -1993	1994 -2000	1966 -1987	1988 -1990	1991 -1993	1994 -2000	1966 -1987	1988 -1990	1991 -1993	1994 -2000	1966 -1987	1988 -1990	1991 -1993	1994 -2000
Heavy-Heavy																
Cal. Reg./Cal. Eng.	$90	$83	$54	$77	$65	$56	$29	$50	0.25	0.22	0.13	0.07	49%	44%	22%	28%
Cal. Reg./Fed. Eng.	$81	$72	$49	$78	$61	$53	$33	$61	0.22	0.19	0.11	0.05	46%	41%	23%	31%
Out of State Reg.	$0	$0	$0	$0	$0	$0	$0	$0	0.47	0.39	0.14	0.07	0%	0%	0%	0%
Medium-Heavy																
Cal. Reg./Cal. Eng.	$78	$73	$66	$77	$40	$34	$30	$39	0.22	0.20	0.13	0.08	38%	34%	24%	27%
Cal. Reg./Fed. Eng.	$75	$71	$66	$77	$38	$33	$30	$39	0.22	0.20	0.13	0.08	36%	33%	24%	27%
Out of State Reg.	$0	$0	$0	$0	$0	$0	$0	$0	0.38	0.33	0.18	0.10	0%	0%	0%	0%
Light-Heavy																
Cal. Reg./Cal. Eng.	$44	$47	$53	$69	$12	$13	$26	$30	0.17	0.17	0.12	0.08	28%	28%	27%	29%
Cal. Reg./Fed. Eng.	$44	$47	$53	$69	$12	$13	$26	$30	0.17	0.17	0.12	0.08	28%	28%	27%	29%
Out of State Reg.	$0	$0	$0	$0	$0	$0	$0	$0	0.21	0.23	0.16	0.11	0%	0%	0%	0%
Transit Bus																
Cal. Reg./Cal. Eng.	$61	$36	$33	$33	$17	$6	$7	$7	0.11	0.07	0.03	0.03	28%	13%	11%	11%
Cal. Reg./Fed. Eng.	$63	$35	$33	$33	$14	$6	$7	$7	0.12	0.07	0.03	0.03	28%	13%	11%	11%

TABLE 7-3. I/M EFFECTIVENESS MODEL RESULTS FOR CASE 1b: $500 COST LIMIT

Vehicle Class	Average Cost Per Vehicle For I/M Repairs				Average Cost Per Vehicle To Correct Tampering				Offensive Smoke Index				Probability of Requiring Repairs			
	1966 -1987	1988 -1990	1991 -1993	1994 -2000	1966 -1987	1988 -1990	1991 -1993	1994 -2000	1966 -1987	1988 -1990	1991 -1993	1994 -2000	1966 -1987	1988 -1990	1991 -1993	1994 -2000
<u>Heavy-Heavy</u>																
Cal. Reg./Cal. Eng.	$70	$54	$39	$54	$70	$62	$35	$55	0.29	0.25	0.14	0.07	46%	42%	21%	26%
Cal. Reg./Fed. Eng.	$64	$56	$36	$56	$66	$59	$41	$68	0.26	0.22	0.12	0.06	43%	39%	22%	28%
Out of State Reg.	$0	$0	$0	$0	$0	$0	$0	$0	0.47	0.39	0.14	0.07	0%	0%	0%	0%
<u>Medium-Heavy</u>																
Cal. Reg./Cal. Eng.	$59	$54	$46	$54	$44	$38	$34	$42	0.24	0.21	0.14	0.08	35%	31%	22%	24%
Cal. Reg./Fed. Eng.	$57	$53	$46	$54	$41	$36	$34	$42	0.24	0.21	0.14	0.08	33%	30%	22%	24%
Out of State Reg.	$0	$0	$0	$0	$0	$0	$0	$0	0.38	0.33	0.18	0.10	0%	0%	0%	0%
<u>Light-Heavy</u>																
Cal. Reg./Cal. Eng.	$30	$32	$36	$40	$13	$16	$30	$32	0.17	0.18	0.12	0.09	26%	25%	25%	26%
Cal. Reg./Fed. Eng.	$30	$32	$36	$40	$13	$16	$30	$32	0.17	0.18	0.12	0.09	26%	25%	25%	26%
Out of State Reg.	$0	$0	$0	$0	$0	$0	$0	$0	0.21	0.23	0.16	0.11	0%	0%	0%	0%
<u>Transit Bus</u>																
Cal. Reg./Cal. Eng.	$48	$26	$23	$23	$19	$6	$8	$8	0.12	0.08	0.03	0.03	25%	12%	9%	9%
Cal. Reg./Fed. Eng.	$49	$25	$23	$23	$16	$6	$8	$8	0.12	0.08	0.03	0.03	26%	11%	9%	9%

TABLE 7-4. I/M EFFECTIVENESS MODEL RESULTS FOR CASE 1c: NO COST LIMIT FOR REPAIRS

	Average Cost Per Vehicle For I/M Repairs				Average Cost Per Vehicle To Correct Tampering				Offensive Smoke Index				Probability of Requiring Repairs			
Vehicle Class	1966 -1987	1988 -1990	1991 -1993	1994 -2000	1966 -1987	1988 -1990	1991 -1993	1994 -2000	1966 -1987	1988 -1990	1991 -1993	1994 -2000	1966 -1987	1988 -1990	1991 -1993	1994 -2000
<u>Heavy-Heavy</u>																
Cal. Reg./Cal. Eng.	$199	$192	$163	$188	$71	$63	$36	$55	0.28	0.24	0.13	0.07	51%	47%	26%	32%
Cal. Reg./Fed. Eng.	$164	$165	$133	$165	$66	$59	$42	$68	0.25	0.21	0.11	0.05	48%	44%	26%	34%
Out of State Reg.	$0	$0	$0	$0	$0	$0	$0	$0	0.47	0.39	0.14	0.07	0%	0%	0%	0%
<u>Medium-Heavy</u>																
Cal. Reg./Cal. Eng.	$240	$233	$227	$239	$44	$38	$36	$43	0.22	0.20	0.13	0.08	41%	37%	28%	31%
Cal. Reg./Fed. Eng.	$237	$232	$227	$239	$42	$37	$36	$43	0.22	0.20	0.13	0.08	39%	36%	28%	31%
Out of State Reg.	$0	$0	$0	$0	$0	$0	$0	$0	0.38	0.33	0.18	0.10	0%	0%	0%	0%
<u>Light-Heavy</u>																
Cal. Reg./Cal. Eng.	$170	$173	$180	$187	$13	$16	$30	$32	0.16	0.17	0.11	0.08	31%	31%	31%	32%
Cal. Reg./Fed. Eng.	$170	$173	$180	$187	$13	$16	$30	$32	0.16	0.17	0.11	0.08	31%	31%	31%	32%
Out of State Reg.	$0	$0	$0	$0	$0	$0	$0	$0	0.21	0.23	0.16	0.11	0%	0%	0%	0%
<u>Transit Bus</u>																
Cal. Reg./Cal. Eng.	$160	$134	$132	$132	$19	$7	$8	$8	0.11	0.07	0.02	0.02	30%	15%	13%	13%
Cal. Reg./Fed. Eng.	$162	$133	$132	$132	$16	$6	$8	$8	0.11	0.07	0.02	0.02	30%	15%	13%	13%

TABLE 7-5. I/M EFFECTIVENESS MODEL RESULTS FOR CASE 1d: NO GASEOUS EMISSIONS MEASUREMENT

Vehicle Class	Average Cost Per Vehicle For I/M Repairs 1966 -1987	1988 -1990	1991 -1993	1994 -2000	Average Cost Per Vehicle To Correct Tampering 1966 -1987	1988 -1990	1991 -1993	1994 -2000	Offensive Smoke Index 1966 -1987	1988 -1990	1991 -1993	1994 -2000	Probability of Requiring Repairs 1966 -1987	1988 -1990	1991 -1993	1994 -2000
<u>Heavy-Heavy</u>																
Cal. Reg./Cal. Eng.	$62	$65	$38	$60	$70	$60	$28	$51	0.29	0.25	0.14	0.07	43%	37%	19%	24%
Cal. Reg./Fed. Eng.	$69	$50	$34	$62	$66	$57	$33	$62	0.26	0.22	0.12	0.06	41%	36%	18%	27%
Out of State Reg.	$0	$0	$0	$0	$0	$0	$0	$0	0.47	0.39	0.14	0.07	0%	0%	0%	0%
<u>Medium-Heavy</u>																
Cal. Reg./Cal. Eng.	$53	$49	$45	$58	$43	$37	$28	$39	0.24	0.21	0.14	0.08	32%	28%	19%	22%
Cal. Reg./Fed. Eng.	$53	$49	$45	$58	$41	$35	$28	$39	0.24	0.21	0.14	0.08	31%	27%	19%	22%
Out of State Reg.	$0	$0	$0	$0	$0	$0	$0	$0	0.38	0.33	0.18	0.10	0%	0%	0%	0%
<u>Light-Heavy</u>																
Cal. Reg./Cal. Eng.	$30	$33	$37	$44	$13	$15	$25	$30	0.17	0.18	0.13	0.09	22%	22%	22%	24%
Cal. Reg./Fed. Eng.	$30	$33	$37	$44	$13	$15	$25	$30	0.17	0.18	0.13	0.09	22%	22%	22%	24%
Out of State Reg.	$0	$0	$0	$0	$0	$0	$0	$0	0.21	0.23	0.16	0.11	0%	0%	0%	0%
<u>Transit Bus</u>																
Cal. Reg./Cal. Eng.	$38	$25	$24	$24	$18	$6	$8	$8	0.12	0.08	0.03	0.03	20%	10%	9%	9%
Cal. Reg./Fed. Eng.	$41	$25	$24	$24	$16	$6	$8	$8	0.13	0.08	0.03	0.03	20%	10%	9%	9%

TABLE 7-6. I/M EFFECTIVENESS MODEL RESULTS FOR CASE 1e: BIENNIAL INSPECTION

	Average Cost Per Vehicle For I/M Repairs				Average Cost Per Vehicle To Correct Tampering				Offensive Smoke Index				Probability of Requiring Repairs			
Vehicle Class	1966 -1987	1988 -1990	1991 -1993	1994 -2000	1966 -1987	1988 -1990	1991 -1993	1994 -2000	1966 -1987	1988 -1990	1991 -1993	1994 -2000	1966 -1987	1988 -1990	1991 -1993	1994 -2000
Heavy-Heavy																
Cal. Reg./Cal. Eng.	$68	$63	$44	$63	$56	$52	$28	$41	0.37	0.31	0.15	0.08	40%	37%	19%	24%
Cal. Reg./Fed. Eng.	$61	$54	$40	$64	$50	$46	$32	$60	0.34	0.28	0.13	0.07	37%	34%	19%	26%
Out of State Reg.	$0	$0	$0	$0	$0	$0	$0	$0	0.47	0.39	0.14	0.07	0%	0%	0%	0%
Medium-Heavy																
Cal. Reg./Cal. Eng.	$61	$56	$53	$63	$37	$33	$28	$32	0.28	0.25	0.15	0.09	32%	29%	21%	23%
Cal. Reg./Fed. Eng.	$59	$55	$53	$63	$33	$30	$28	$32	0.28	0.25	0.15	0.09	30%	27%	21%	23%
Out of State Reg.	$0	$0	$0	$0	$0	$0	$0	$0	0.38	0.33	0.18	0.10	0%	0%	0%	0%
Light-Heavy																
Cal. Reg./Cal. Eng.	$35	$37	$43	$48	$11	$12	$23	$23	0.18	0.20	0.14	0.09	23%	23%	23%	24%
Cal. Reg./Fed. Eng.	$35	$37	$43	$48	$11	$12	$23	$23	0.18	0.20	0.14	0.09	23%	23%	23%	24%
Out of State Reg.	$0	$0	$0	$0	$0	$0	$0	$0	0.21	0.23	0.16	0.11	0%	0%	0%	0%
Transit Bus																
Cal. Reg./Cal. Eng.	$45	$28	$27	$27	$19	$5	$7	$7	0.13	0.08	0.03	0.03	23%	11%	9%	9%
Cal. Reg./Fed. Eng.	$46	$27	$27	$27	$15	$5	$7	$7	0.14	0.08	0.03	0.03	22%	10%	9%	9%

TABLE 7-7. I/M EFFECTIVENESS MODEL RESULTS FOR CASE 1f: CURRENT SMOG CHECK LAW

Vehicle Class	Average Cost Per Vehicle For I/M Repairs 1966 -1987	1988 -1990	1991 -1993	1994 -2000	Average Cost Per Vehicle To Correct Tampering 1966 -1987	1988 -1990	1991 -1993	1994 -2000	Offensive Smoke Index 1966 -1987	1988 -1990	1991 -1993	1994 -2000	Probability of Requiring Repairs 1966 -1987	1988 -1990	1991 -1993	1994 -2000
Heavy-Heavy																
Cal. Reg./Cal. Eng.	$9	$8	$3	$3	$79	$71	$43	$75	0.40	0.34	0.17	0.09	38%	35%	18%	23%
Cal. Reg./Fed. Eng.	$8	$7	$3	$2	$73	$65	$47	$90	0.37	0.31	0.15	0.08	36%	32%	19%	25%
Out of State Reg.	$0	$0	$0	$0	$0	$0	$0	$0	0.47	0.39	0.14	0.07	0%	0%	0%	0%
Medium-Heavy																
Cal. Reg./Cal. Eng.	$7	$6	$3	$3	$55	$48	$48	$51	0.31	0.27	0.16	0.10	29%	26%	20%	22%
Cal. Reg./Fed. Eng.	$6	$6	$3	$3	$51	$46	$48	$51	0.31	0.27	0.16	0.10	28%	26%	20%	22%
Out of State Reg.	$0	$0	$0	$0	$0	$0	$0	$0	0.38	0.33	0.18	0.10	0%	0%	0%	0%
Light-Heavy																
Cal. Reg./Cal. Eng.	$3	$3	$3	$3	$23	$26	$43	$49	0.20	0.22	0.15	0.10	21%	21%	22%	23%
Cal. Reg./Fed. Eng.	$3	$3	$3	$3	$23	$26	$43	$49	0.20	0.22	0.15	0.10	21%	21%	22%	23%
Out of State Reg.	$0	$0	$0	$0	$0	$0	$0	$0	0.21	0.23	0.16	0.11	0%	0%	0%	0%
Transit Bus																
Cal. Reg./Cal. Eng.	$5	$2	$2	$2	$31	$14	$16	$16	0.15	0.09	0.03	0.03	21%	10%	9%	9%
Cal. Reg./Fed. Eng.	$5	$2	$2	$2	$29	$13	$16	$16	0.15	0.09	0.03	0.03	20%	10%	9%	9%

RADIAN CORPORATION

TABLE 7-8. I/M EFFECTIVENESS MODEL RESULTS FOR CASE 2: IN-USE INSPECTION WITH $1,000 COST LIMIT

Vehicle Class	Average Cost Per Vehicle For I/M Repairs				Average Cost Per Vehicle To Correct Tampering				Offensive Smoke Index				Probability of Requiring Repairs				Probability of Fine for Tampering			
	1966 -1987	1988 -1990	1991 -1993	1994 -2000	1966 -1987	1988 -1990	1991 -1993	1994 -2000	1966 -1987	1988 -1990	1991 -1993	1994 -2000	1966 -1987	1988 -1990	1991 -1993	1994 -2000	1966 -1987	1988 -1990	1991 -1993	1994 -2000
Heavy-Heavy																				
Cal. Reg./Cal. Eng.	$104	$91	$67	$90	$37	$33	$23	$42	0.17	0.16	0.10	0.05	44%	38%	23%	29%	8%	7%	3%	5%
Cal. Reg./Fed. Eng.	$91	$79	$59	$88	$36	$32	$27	$62	0.15	0.14	0.08	0.04	41%	36%	22%	30%	8%	7%	4%	6%
Out of State Reg.	$74	$64	$44	$73	$35	$32	$27	$62	0.24	0.21	0.09	0.04	38%	34%	20%	28%	8%	7%	4%	6%
Medium-Heavy																				
Cal. Reg./Cal. Eng.	$99	$89	$78	$90	$23	$20	$25	$33	0.16	0.15	0.10	0.06	37%	33%	25%	28%	5%	4%	3%	4%
Cal. Reg./Fed. Eng.	$99	$89	$78	$90	$22	$20	$25	$33	0.16	0.15	0.10	0.06	36%	32%	25%	28%	5%	4%	3%	4%
Out of State Reg.	$98	$89	$77	$89	$22	$20	$25	$33	0.23	0.20	0.12	0.07	36%	32%	25%	28%	5%	4%	3%	4%
Light-Heavy																				
Cal. Reg./Cal. Eng.	$61	$63	$63	$70	$6	$8	$22	$26	0.14	0.14	0.09	0.07	28%	28%	28%	30%	2%	2%	4%	5%
Cal. Reg./Fed. Eng.	$61	$63	$63	$70	$6	$8	$22	$26	0.14	0.14	0.09	0.07	28%	28%	28%	30%	2%	2%	4%	5%
Out of State Reg.	$61	$62	$62	$69	$6	$8	$22	$26	0.16	0.17	0.11	0.07	28%	28%	28%	29%	2%	2%	4%	5%
Transit Bus																				
Cal. Reg./Cal. Eng.	$64	$44	$42	$42	$9	$4	$6	$6	0.09	0.06	0.02	0.02	23%	15%	12%	12%	2%	1%	1%	1%
Cal. Reg./Fed. Eng.	$65	$44	$42	$42	$8	$3	$6	$6	0.10	0.06	0.02	0.02	24%	15%	12%	12%	2%	1%	1%	1%

RADIAN CORPORATION

TABLE 7-9. I/M EFFECTIVENESS MODEL RESULTS FOR CASE 2a: IN-USE INSPECTION WITH NO COST LIMIT

	Average Cost Per Vehicle For I/M Repairs				Average Cost Per Vehicle To Correct Tampering				Offensive Smoke Index				Probability of Requiring Repairs				Probability of Fine for Tampering			
Vehicle Class	1966 -1987	1988 -1990	1991 -1993	1994 -2000	1966 -1987	1988 -1990	1991 -1993	1994 -2000	1966 -1987	1988 -1990	1991 -1993	1994 -2000	1966 -1987	1988 -1990	1991 -1993	1994 -2000	1966 -1987	1988 -1990	1991 -1993	1994 -2000
<u>Heavy-Heavy</u>																				
Cal. Reg./Cal. Eng.	$264	$250	$224	$253	$37	$33	$23	$42	0.16	0.14	0.09	0.04	47%	41%	26%	33%	8%	7%	3%	5%
Cal. Reg./Fed. Eng.	$212	$199	$177	$214	$36	$32	$27	$52	0.14	0.13	0.08	0.03	44%	39%	25%	34%	8%	7%	4%	6%
Out of State Reg.	$170	$159	$137	$174	$35	$32	$27	$52	0.24	0.20	0.09	0.03	41%	36%	22%	32%	8%	7%	4%	6%
<u>Medium-Heavy</u>																				
Cal. Reg./Cal. Eng.	$331	$321	$309	$325	$23	$20	$25	$33	0.14	0.13	0.09	0.05	41%	36%	29%	33%	5%	4%	3%	4%
Cal. Reg./Fed. Eng.	$331	$321	$309	$325	$22	$20	$25	$33	0.14	0.13	0.09	0.06	40%	36%	29%	33%	5%	4%	3%	4%
Out of State Reg.	$317	$306	$295	$310	$22	$20	$25	$33	0.22	0.20	0.12	0.06	40%	36%	29%	32%	5%	4%	3%	4%
<u>Light-Heavy</u>																				
Cal. Reg./Cal. Eng.	$242	$244	$245	$254	$6	$8	$22	$26	0.12	0.13	0.08	0.05	32%	33%	32%	34%	2%	2%	4%	5%
Cal. Reg./Fed. Eng.	$242	$244	$245	$254	$6	$8	$22	$26	0.12	0.13	0.08	0.05	32%	33%	32%	34%	2%	2%	4%	5%
Out of State Reg.	$233	$235	$236	$245	$6	$8	$22	$26	0.15	0.16	0.10	0.07	32%	33%	32%	34%	2%	2%	4%	5%
<u>Transit Bus</u>																				
Cal. Reg./Cal. Eng.	$206	$184	$183	$183	$9	$4	$5	$6	0.09	0.06	0.02	0.02	26%	17%	15%	15%	2%	1%	1%	1%
Cal. Reg./Fed. Eng.	$208	$184	$183	$183	$8	$3	$6	$6	0.09	0.06	0.02	0.02	27%	17%	15%	15%	2%	1%	1%	1%

total annual maintenance costs for a heavy truck. Thus, the I/M program would not result in a major increase in repair costs. Similarly, even in the in-use inspection scenarios, only about 25 to 50 percent of the trucks operating would be required to be repaired in a given year. The probability of receiving a fine is also very low--ranging from 1 to 8 percent, depending on the model year and vehicle class. Thus, this program would not pose a crippling burden either for the individual truck owner or for the trucking industry.

8.0 MODEL RESULTS: PROGRAM COSTS, COST-EFFECTIVENESS, AND SMOKE

As discussed in Section Four, the costs of an I/M program can be divided into those costs borne by the vehicle owner and government enforcement and administration costs. This section presents our estimates of the aggregate cost of each of our I/M scenarios to vehicle owners, and to society as a whole, as well as the cost-effectiveness of each approach for particulate emissions control. Costs and cost-effectiveness are calculated for three years spanning the time range of interest: 1990, ~~1995, and~~ 2000.

8.1 Program Costs to Vehicle Owners

The costs of the I/M program to a vehicle owner consist of the following:

- State charges for a Smog Certificate (including the cost of inspection in centralized programs);
- Private garage inspection fee for decentralized programs;
- Value of truck and driver time spent undergoing inspection;
- Cost of any additional repairs required by the I/M program, over and above the repairs that the owner would make anyway;
- Cost of correcting any tampering detected;
- Cost of reinspection after repairs;
- Value of truck and driver time lost due to repairs and reinspection;
- Any fines imposed for tampering or excessive smoke.

In order to estimate the overall costs of each I/M scenario, we calculated the total cost of each of these components for each class of vehicles included in the model. Costs were calculated by multiplying the number of vehicles affected by each cost element by the estimated cost per vehicle. The results of these calculations are presented in Tables 8-1 through 8-3. The details of the assumptions made in each case are discussed below. Estimates of the number of vehicles included in each class and model year group for the three program years of 1990, 1995, and 2000 are given in the Appendix.

Inspection costs--For Cases 1, 1b, 1c, 1e, and 1f, the cost of an initial I/M inspection for a medium-heavy or heavy-heavy vehicle was assumed to be $75, plus a $17 fee the Smog Certificate, as discussed in Section 4.2.1. For light-heavy duty vehicles, the inspection fee was taken at $60. For case 1d (no gaseous emissions) the inspection fees were assumed to be $10 lower, reflecting the lower capital and operating costs of the inspection setup. The fee for reinspection after repairs was assumed to be the same as for the initial inspection in each case.

For Case 1a (central inspection), the inspection fee was taken at $100 per vehicle, regardless of size, based on the discussion in Section 4.2.2. Reinspections were assumed to be free of charge. For Cases 2 and 2a, no fees were assumed for the initial inspection. A reinspection fee of $40 was assumed, however. This would cover the cost of a fast opacity check at an authorized garage.

Total inspection costs were calculated by multiplying the costs per vehicle discussed above by the total number of vehicles subject to inspection. For the initial inspection, this is simply the number of California-registered vehicles. For reinspection, the number of vehicles subject to inspection in each class was multiplied by the I/M failure rate (probability of requiring repairs) for that class to arrive at the total number being reinspected.

TABLE 8-1. SUMMARY OF I/M PROGRAM COSTS TO VEHICLE OWNERS: 1990

CASE	COST OF SMOG CERTIFICATES	COST OF PRIVATE INSPECTION	PROB. OF REQUIRING REPAIRS	COST OF REPAIRS	COST TO CORRECT TAMPERING	TOTAL DIRECT COSTS	TIME LOST DUE TO INSPECTION	TIME LOST DUE TO REPAIRS	TOTAL TIME LOST	TOTAL COSTS	FINES FOR TAMPERING
1	$4,435,882	$23,763,600	34%	$15,887,867	$8,980,541	$53,087,891	$9,031,758	$10,776,392	$29,808,151	$82,876,044	$0
1a	26,093,424	0	34%	16,284,320	8,077,986	50,465,730	19,733,668	18,893,912	38,627,581	89,093,313	$0
1b	4,435,882	23,305,723	32%	12,128,394	8,898,044	48,768,043	19,031,758	9,959,357	28,991,116	77,759,161	$0
1c	4,435,882	24,320,816	38%	49,217,271	8,980,541	86,954,508	19,031,758	11,780,425	30,812,183	117,766,694	$0
1d	4,435,882	19,421,320	28%	11,263,922	8,792,946	43,914,071	19,031,758	9,025,846	28,057,605	71,971,677	$0
1e	4,435,882	11,881,800	34%	7,943,934	4,490,270	28,751,886	9,516,879	5,388,196	14,904,075	82,876,044	$0
1f	782,803	11,193,787	27%	677,289	5,678,578	18,332,455	9,516,879	4,186,971	13,702,850	64,070,813	$0
2	0	4,063,272	33%	23,879,352	5,732,000	33,674,624	7,737,105	13,977,864	21,714,969	55,389,593	$13,338,805
2a	0	4,518,785	37%	77,645,230	5,732,000	87,896,015	7,737,105	15,451,716	23,188,821	111,084,836	$13,338,806

TABLE 8-2. SUMMARY OF I/M PROGRAM COSTS TO VEHICLE OWNERS: 1995

CASE	COST OF SMOG CERTIFICATES	COST OF PRIVATE INSPECTION	PROB. OF REQUIRING REPAIRS	COST OF REPAIRS	COST TO CORRECT TAMPERING	TOTAL DIRECT COSTS	TIME LOST DUE TO INSPECTION	TIME LOST DUE TO REPAIRS	TOTAL TIME LOST	TOTAL COSTS	FINES FOR TAMPERING
1	$5,881,846	$30,039,843	31%	$20,082,496	$11,433,035	$67,437,120	$24,581,497	$12,748,250	$37,329,746	$104,766,866	$0
1a	34,597,819	0	31%	20,887,703	10,135,528	65,421,149	25,298,907	22,238,321	47,535,228	112,956,378	0
1b	5,881,846	29,440,030	28%	14,841,206	11,323,208	61,486,091	24,581,497	11,658,302	36,239,798	97,725,892	0
1c	5,881,846	30,802,985	34%	64,840,069	11,433,035	112,957,735	24,581,497	14,145,314	38,726,810	151,684,546	0
1d	5,881,846	24,451,517	25%	14,600,358	10,599,662	55,433,383	24,581,497	10,468,959	35,050,456	90,483,841	0
1e	5,881,846	14,409,124	25%	8,169,452	4,424,717	59,866,232	12,280,748	5,280,178	35,141,852	95,008,086	0
1f	1,037,836	14,249,570	24%	706,741	7,646,344	47,281,184	12,280,748	4,897,021	34,575,538	81,856,724	0
2	0	4,777,367	30%	29,044,964	8,310,305	42,132,636	9,725,269	15,621,763	25,347,032	67,479,668	15,953,881
2a	0	5,398,877	34%	99,949,682	8,310,305	113,658,664	9,725,269	17,561,889	27,287,158	140,945,822	15,953,881

TABLE 8-3. SUMMARY OF I/M PROGRAM COSTS TO VEHICLE OWNERS: 2000

CASE	COST OF SMOG CERTIFICATES	COST OF PRIVATE INSPECTION	PROB. OF REQUIRING REPAIRS	COST OF REPAIRS	COST TO CORRECT TAMPERING	TOTAL DIRECT COSTS	TIME LOST DUE TO INSPECTION	TIME LOST DUE TO REPAIRS	TOTAL TIME LOST	TOTAL COSTS	FINES FOR TAMPERING
1	$7,022,874	$35,164,562	28%	$24,343,620	$14,331,153	$80,862,209	$29,053,324	$14,484,061	$43,537,385	$124,399,597	$0
1a	41,311,026	0	29%	25,234,724	12,808,151	79,353,901	29,796,824	25,265,490	55,062,314	134,416,217	0
1b	7,022,874	34,430,727	27%	17,682,971	14,230,323	73,366,895	29,053,324	13,143,114	42,196,438	115,563,336	0
1c	7,022,874	36,109,859	33%	78,156,216	14,331,153	135,620,102	29,053,324	16,223,007	45,276,332	180,896,436	0
1d	7,022,874	28,622,469	24%	18,218,646	13,173,854	67,037,843	29,053,324	11,887,021	40,940,345	107,978,191	0
1e	7,022,874	16,896,333	24%	10,099,801	5,396,751	39,415,759	14,526,662	5,999,517	20,526,179	112,881,004	0
1f	1,239,331	16,745,012	23%	716,728	9,987,539	28,688,610	14,526,662	5,726,492	20,253,155	97,883,532	0
2	0	5,470,096	29%	34,454,149	11,662,714	51,586,959	11,380,088	17,429,497	28,809,585	80,396,543	19,312,831
2a	0	6,238,344	33%	119,122,743	11,662,714	137,023,802	11,380,088	19,801,331	31,181,419	168,205,220	19,312,831

Repair Costs--The average costs per vehicle for repairs and for the correction of tampering were calculated by the I/M effects model described in Section Five. These data were presented in Tables 7-1 through 7-9 above. To arrive at the total costs for each vehicle class, it was necessary only to multiply the average costs per vehicle by the total number of vehicles in each class.

Indirect Costs--The value of vehicle and driver time lost due to I/M inspections and repairs was calculated using the approach described in Section 4.2.3. The initial I/M inspection was assumed to require three hours of vehicle and driver time per vehicle, at a cost of $90 for heavy-heavy and medium-heavy duty vehicles, and $60 for light-heavy duty vehicles. Transit buses were assumed to lose no time on the inspection, as this would be done on-site as part of the maintenance program.

Repairs required as a result of the I/M program were assumed to consume an additional day of vehicle time and two hours of driver time for vehicles failing the I/M test, resulting in a cost of $120 for heavy-heavy and medium heavy vehicles and buses, and $70 for light-heavy duty vehicles. For the decentralized programs, it was assumed that most such repairs would be done at the same shop as the inspection, so that there would be no additional indirect costs for reinspection. For Case 1a (centralized inspection), an three hours of vehicle and driver time was assumed for the repeat inspection.

Fines--As discussed in Section Five, the I/M effects model estimated the fraction of the vehicle fleet that would be fined for tampering under the two in-use inspection scenarios. These estimates were based on the assumption that about half of the detected cases of tampering would result in fines. To estimate the total fines levied on each class, the fraction of vehicles of each class receiving fines was multiplied by the total number of vehicles in that class, and by the nominal amount of the fine--$1,000.

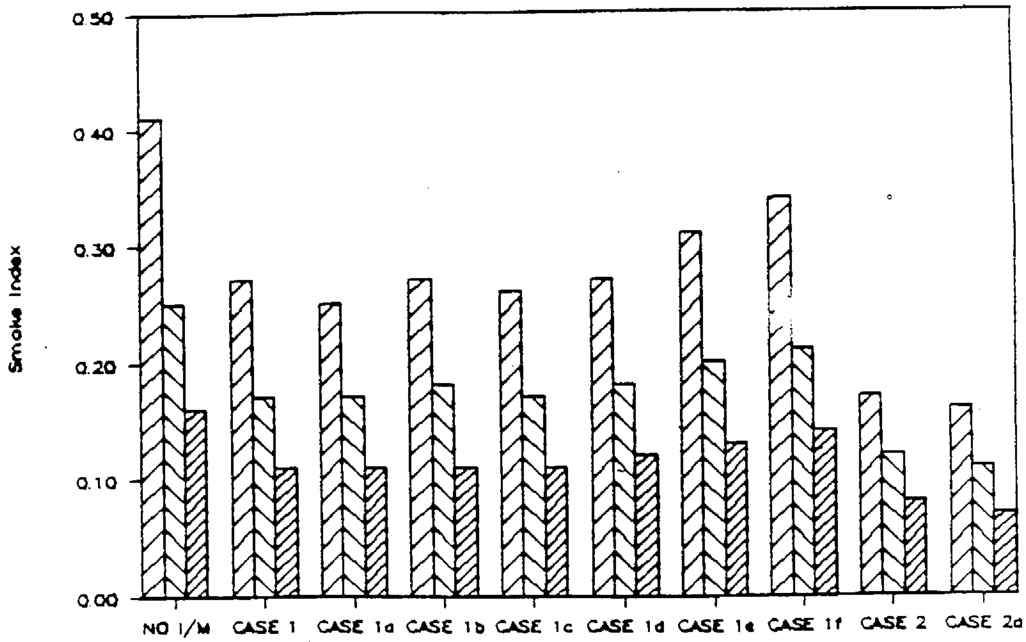
Offensive Smoke--Because of the computational structure of the model, it was most convenient to calculate fleetwide average offensive smoke indices at the same time as the total costs. Figure 8-1 compares the resulting average smoke indices for each scenario with those for the case with no I/M program. As this figure indicates, the smoke estimates more or less follow the particulate estimates presented in Section Six. All of the annual inspection cases produce a 30-40 percent reduction in offensive smoke incidence, while the biennial inspections are less effective. The in-use smoke enforcement programs offer the greatest reductions, however, resulting in a 50-60 percent decrease in offensive smoke.

As Figure 8-1 also shows, the offensive smoke indices for all of the scenarios, including the baseline, are projected to decline sharply between 1990 and 2000, due to the increasingly stringent particulate standards during that period. Therefore, the quality-of-life benefits of reducing offensive smoke via an I/M program would also decline, unless people become proportionally more sensitive to offensive smoke as the incidence decreases.

8.2 Social Costs and Cost-Effectiveness

The total costs to society of an I/M program include the costs to the vehicle owner, as presented in Tables 8-1 through 8-3, fuel costs or savings, and the costs to the government of administering and enforcing the program. Government administration and enforcement costs were estimated in Section Four. Fines and Smog Certificate fees paid by the vehicle owner are not included in social costs, as these represent a transfer payment rather than an actual consumption of resources. The amount of the fine or fee appears as a component of the truck-owner's cost, but the cost to government is reduced by the same amount. Except for Case 1f (current Smog Check Law), the fees or fines charged in each of the I/M scenarios considered here are at least adequate to offset the costs to the government.

Offensive Smoke Index



% Reduction in Offensive Smoke Index

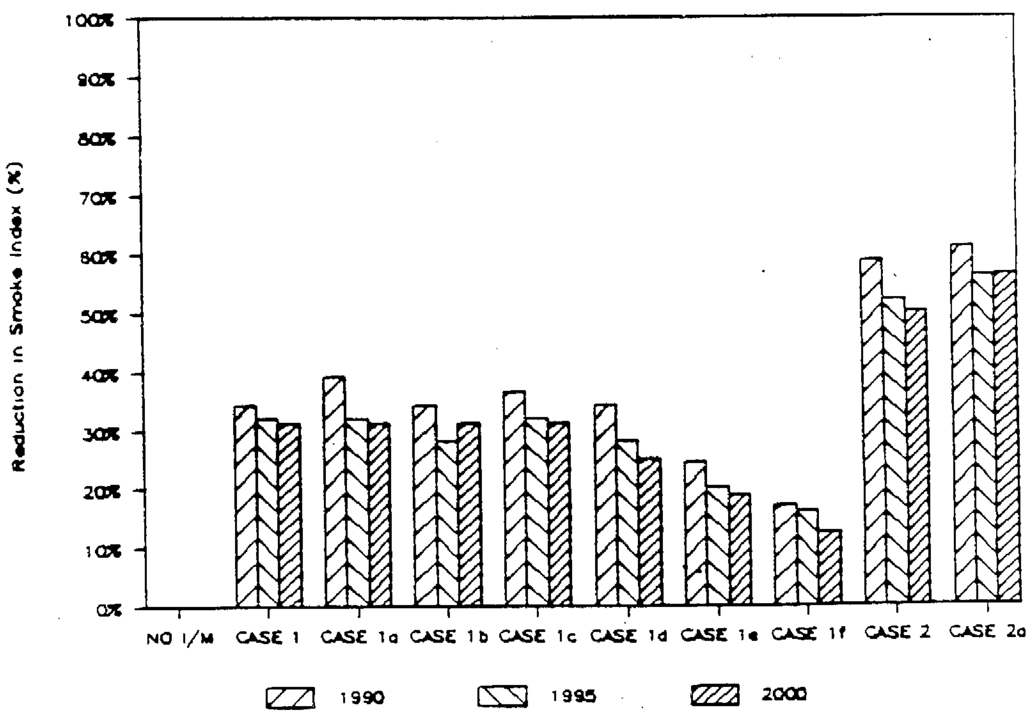


Figure 8-1. Comparison of I/M Scenarios: Reduction of Offensive Smoke Due to I/M

The resulting social cost calculations for the program years 1990, 1995, and 2000 are shown in Tables 8-4 through 8-6. These tables also show the net reduction in emissions due to each program, and the cost-effectiveness of each program for particulate emissions control. Overall and cost-effectiveness estimates for each scenario are summarized in Figure 8-2.

To calculate the cost-effectiveness of an emissions control strategy-such as I/M--which affects more than one pollutant requires that some assumptions be made as to the proper allocation of costs between the different pollutants. For our calculations, we assigned each program a credit of $4,000 per ton of NO_x or HC reduced, and assigned the remaining costs of the program to particulate control. Making these assumptions, we were able to calculate the cost-effectiveness of each program as a particulate control measure, treating the HC and NO_x reduction benefits as side-effects. The value of $4,000 per ton of HC and NO_x eliminated is fairly typical of other ongoing emission control initiatives in California, although many approaches with higher and lower cost-effectiveness values have also been recommended.

As Figure 8-2 shows, the most cost-effective I/M program scenario by our calculations is Case 2, followed by Case 1e. Case 2 also results in the second largest reduction in particulate emissions (after Case 2a), and the third-largest NO_x reduction. This scenario thus appears clearly preferable overall. Cases 2 and 1e are followed by the other cost-limited periodic inspection programs. These are grouped fairly closely in cost-effectiveness and overall results, although Case 1a (centralized inspection) has somewhat of an advantage. This shows that centralized inspection is superior to even an effectively administered and enforced decentralized program. The advantage of centralized inspection over a less vigorously enforced decentralized program would be much greater.

By far the highest costs-per-ton of emissions control are calculated for Case 1c, without a repair cost limit. This is due to the very high costs of engine overhaul included in these cases. These calculations overestimate the actual economic costs somewhat, since overhauling an engine increases its

TABLE 8-4. COSTS AND COST EFFECTIVENESS OF ALTERNATIVE I/M PROGRAM DESIGNS: 1990

	Case 1	Case 1a	Case 1b	Case 1c	Case 1d	Case 1e	Case 1f	Case 2	Case 2a
Program Cost (millions of dollars)									
Costs to Truck Owners									
Smog Certificates	4.44	26.09	4.44	4.44	4.44	4.44	0.78	0.00	0.00
Private Inspections	23.76	0.00	23.31	24.32	19.42	11.88	11.19	4.06	4.52
Non-Tampering Repairs	15.89	16.29	12.13	49.22	11.26	7.94	0.68	23.88	77.65
Tampering Repairs	8.98	8.08	8.90	8.98	8.79	4.49	5.68	5.73	5.73
Lost Time	29.81	38.63	28.99	30.81	28.06	14.90	13.70	21.71	23.19
Fines	0.00	0.00	0.00	0.00	0.00	0.00	0.00	13.34	13.34
Fuel Consumption	-8.2	-8.8	-7.6	-8.9	-8.8	-5.2	-2.4	-16.2	-17.2
Total Cost to Owners	74.7	80.3	70.2	108.9	63.1	38.4	29.6	52.5	107.2
Costs to Government									
Program Costs	4.4	26.7	4.4	4.4	4.4	4.4	4.4	6.8	6.8
Fees and Fines	-4.4	-26.1	-4.4	-4.4	-4.4	-4.4	-0.8	-13.3	-13.3
Total Cost to Government	0.0	0.6	0.0	0.0	0.0	0.0	3.7	-6.5	-6.5
Total Social Cost	74.7	80.9	70.2	108.9	63.1	38.4	33.3	46.0	100.6
Emission Reductions (tons/day)									
Oxides of Nitrogen	23.3	26.4	23.1	23.5	12.7	16.3	13.6	11.3	11.0
Unburned Hydrocarbons	3.3	3.2	2.5	5.4	1.9	2.0	-0.3	8.7	12.6
Particulate Matter	16.7	17.9	15.5	18.1	15.7	11.4	6.7	31.1	33.6
Cost-Effectiveness ($/Ton)									
NOx	$4,000	$4,000	$4,000	$4,000	$4,000	$4,000	$4,000	$4,000	$4,000
HC	$4,000	$4,000	$4,000	$4,000	$4,000	$4,000	$4,000	$4,000	$4,000
PM	$5,869	$5,764	$5,779	$10,087	$7,273	$2,836	$5,661	$1,489	$5,388
Cost-Effectiveness ($/ton PM)* W/O Indirect costs and savings	$2,330	$1,210	$2,000	$6,770	$3,930	$502	$1,066	(Neg)**	$3,816

* Indirect costs are lost time and fuel consumption.

** Negative cost after taking NO_x and HC credits.

TABLE 8-5. COSTS AND COST EFFECTIVENESS OF ALTERNATIVE I/M PROGRAM DESIGNS: 1995

	Case 1	Case 1a	Case 1b	Case 1c	Case 1d	Case 1e	Case 1f	Case 2	Case 2a
Program Cost (millions of dollars)									
Costs to Truck Owners									
Smog Certificates	5.88	34.60	5.88	5.88	5.88	5.88	1.04	0.00	0.00
Private Inspections	30.04	0.00	29.44	30.80	24.45	14.41	14.25	4.78	5.40
Non-Tampering Repairs	20.08	20.69	14.84	64.84	14.50	8.16	0.71	29.04	99.95
Tampering Repairs	11.43	10.14	11.32	11.43	10.60	4.42	7.65	8.31	8.31
Lost Time	37.33	47.54	36.24	38.73	35.05	17.57	17.29	25.35	27.29
Fines	0.00	0.00	0.00	0.00	0.00	0.00	0.00	15.95	15.95
Fuel Consumption	-1.1	-0.4	-0.6	-1.5	-1.9	-0.5	1.2	-4.3	-5.1
Total Cost to Owners	103.7	112.5	97.1	150.1	88.6	50.0	42.1	79.1	151.8
Costs to Government									
Program Costs	5.9	34.6	5.9	5.9	5.9	5.9	5.9	9.0	9.0
Fees and Fines	-5.9	-34.6	-5.9	-5.9	-5.9	-5.9	-1.0	-16.0	-16.0
Total Cost to Government	0.0	0.0	0.0	0.0	0.0	0.0	4.8	-7.0	-7.0
Total Social Cost	103.7	112.5	97.1	150.1	88.6	50.0	47.0	72.1	144.8
Emission Reductions (tons/day)									
Oxides of Nitrogen	28.5	34.0	28.4	28.7	18.5	19.5	16.6	25.0	24.9
Unburned Hydrocarbons	5.1	5.3	4.4	6.7	4.0	3.4	1.2	11.5	14.5
Particulate Matter	13.1	14.2	12.2	14.3	12.2	9.0	5.3	24.6	26.7
Cost-Effectiveness ($/ton)									
NOx	$4,000	$4,000	$4,000	$4,000	$4,000	$4,000	$4,000	$4,000	$4,000
HC	$4,000	$4,000	$4,000	$4,000	$4,000	$4,000	$4,000	$4,000	$4,000
PM	$11,396	$10,626	$11,042	$18,855	$12,568	$5,038	$10,868	$2,101	$8,959
Cost-Effectiveness ($/ton PM)* W/O Indirect costs and savings	$3,825	$1,546	$3,049	$11,731	$5,102	(Neg)**	$1,342	(Neg)**	$5,046

* Indirect costs are lost time and fuel consumption.

** Negative cost after taking NO_x and HC credits.

TABLE 8-6. COSTS AND COST EFFECTIVENESS OF ALTERNATIVE I/M PROGRAM DESIGNS: 2000

	Case 1	Case 1a	Case 1b	Case 1c	Case 1d	Case 1e	Case 1f	Case 2	Case 2a
Program Cost (millions of dollars)									
Costs to Truck Owners									
Smog Certificates	7.02	41.31	7.02	7.02	7.02	7.02	1.24	0.00	0.00
Private Inspections	35.16	0.00	34.43	36.11	28.62	16.90	16.75	5.47	6.24
Non-Tampering Repairs	24.34	25.23	17.68	78.16	18.22	10.10	0.72	34.45	119.12
Tampering Repairs	14.33	12.81	14.23	14.33	13.17	5.40	9.99	11.66	11.66
Lost Time	43.54	55.06	42.20	45.28	40.94	20.53	20.25	28.81	31.18
Fines	0.00	0.00	0.00	0.00	0.00	0.00	0.00	19.31	19.31
Fuel Consumption	4.8	6.5	5.1	4.5	4.0	3.5	4.2	5.8	5.2
Total Cost to Owners	129.2	140.9	120.7	185.4	111.9	63.4	53.1	105.5	192.8
Costs to Government									
Program Costs	7.0	41.3	7.0	7.0	7.0	7.0	7.0	10.7	10.7
Fees and Fines	-7.0	-41.3	-7.0	-7.0	-7.0	-7.0	-1.2	-19.3	-19.3
Total Cost to Government	0.0	0.0	0.0	0.0	0.0	0.0	5.8	-8.6	-8.6
Total Social Cost	129.2	140.9	120.7	185.4	111.9	63.4	58.9	96.9	184.2
Emission Reductions (tons/day)									
Oxides of Nitrogen	33.2	40.4	33.1	33.4	23.0	22.6	19.3	34.6	34.6
Unburned Hydrocarbons	7.1	7.6	6.4	8.5	6.2	4.8	2.4	14.9	17.5
Particulate Matter	12.0	13.1	11.2	13.0	11.2	8.2	5.0	22.8	24.6
Cost-Effectiveness ($/ton)									
NOx	$4,000	$4,000	$4,000	$4,000	$4,000	$4,000	$4,000	$4,000	$4,000
HC	$4,000	$4,000	$4,000	$4,000	$4,000	$4,000	$4,000	$4,000	$4,000
PM	$16,102	$14,734	$15,406	$26,145	$16,983	$7,805	$15,087	$2,942	$12,023
Cost-Effectiveness ($/ton PM)* W/O Indirect costs and savings	$5,033	$1,908	$3,836	$15,666	$5,983	(Neg)**	$1,606	(Neg)**	$5,823

* Indirect costs are lost time and fuel consumption.

** Negative cost after taking NO_x and HC credits.

Cost-Effectiveness for Particulate Control

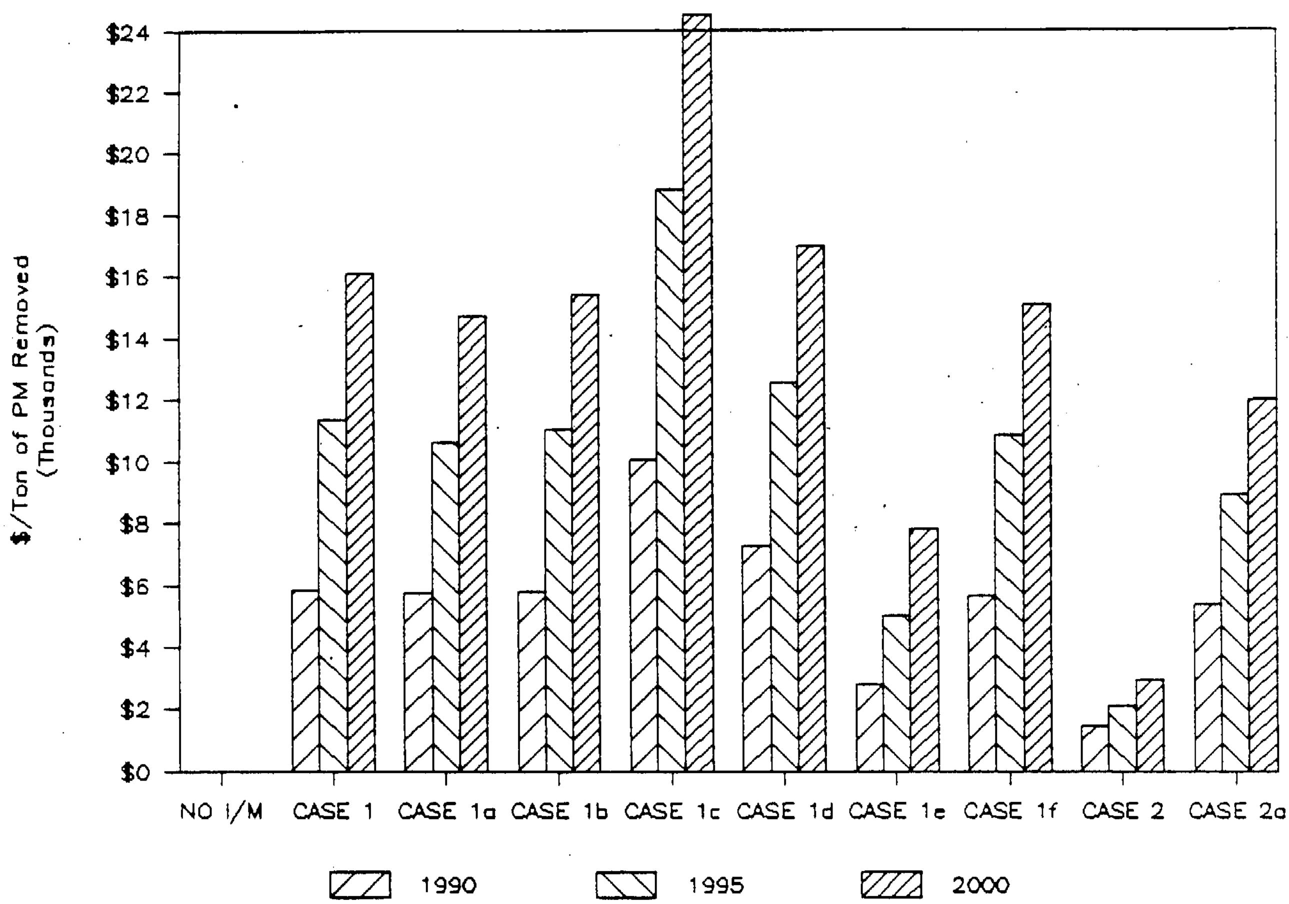


Figure 8-2. Comparison of I/M Scenarios: Cost Effectiveness

value and useful life. Nonetheless, it appears that some reasonable limit on repair costs is needed in a heavy-duty diesel I/M program in order to keep overall program costs and cost-effectiveness reasonable.

The cost-effectiveness calculations shown in the tables include an explicit accounting for "indirect" costs and benefits to the truck owner. These include lost truck and driver time, and fuel consumption effects. These are a large fraction of the total costs of the program. For compatibility with some other cost-effectiveness estimates for I/M programs, we also calculated the cost-effectiveness omitting these cost elements. Omitting these elements reduces the calculated cost of the program considerably--to the point that the cost is less than the credit for HC and NO_x reductions, in some cases.

9.0 BIBLIOGRAPHY

California Highway Patrol (1986) Commercial Vehicle Activities, Sacramento, CA.

Weaver, C.S., C. Miller, and L.A. Nelowet (1984) Particulate Control Technology and Particulate Emissions Standards for Heavy-Duty Diesel Engines, report under EPA Contract No. 68-01-6543, Energy and Resource Consultants, Inc., Boulder, CO.

APPENDIX A

TABLE A-1: EMISSIONS AND FUEL-CONSUMPTION MODEL RESULTS FOR SCENARIO 1

	OXIDES OF NITROGEN (TPD)				UNBURNED HYDROCARBONS (TPD)				PARTICULATE MATTER (TPD)				FUEL CONSUMPTION (MM GAL/YR)			
CALENDAR YEAR	TOTAL EMISSIONS	EXCESS EMISSIONS	CHANGE FROM BASELINE	% CHANGE FROM BASELINE	TOTAL EMISSIONS	EXCESS EMISSIONS	CHANGE FROM BASELINE	% CHANGE FROM BASELINE	TOTAL EMISSIONS	EXCESS EMISSIONS	CHANGE FROM BASELINE	% CHANGE FROM BASELINE	TOTAL FUEL USE	EXCESS FUEL USE	CHANGE FROM BASELINE	% CHANGE FROM BASELINE
1985	490.3	7.0	-20.6	-4.0%	91.6	32.1	-3.2	-3.3%	100.7	50.1	-16.9	-14.4%	1,362	38.1	-10.6	-0.8%
1986	518.6	7.5	-21.1	-3.9%	99.0	34.7	-3.4	-3.3%	109.2	54.3	-17.8	-14.0%	1,457	41.9	-11.0	-0.7%
1987	521.8	7.5	-21.1	-3.9%	101.0	35.4	-3.4	-3.3%	112.3	55.8	-18.5	-14.1%	1,475	42.3	-11.2	-0.8%
1988	529.9	9.0	-21.9	-4.0%	100.1	34.9	-3.4	-3.3%	110.3	54.6	-18.0	-14.0%	1,486	41.7	-10.9	-0.7%
1989	539.7	10.7	-22.8	-4.1%	98.6	34.2	-3.4	-3.3%	107.2	52.7	-17.3	-13.9%	1,493	41.0	-10.6	-0.7%
1990	541.7	11.9	-23.3	-4.1%	97.4	33.6	-3.3	-3.3%	105.4	51.8	-16.7	-13.7%	1,501	40.4	-10.3	-0.7%
1991	537.6	14.6	-24.5	-4.4%	93.6	33.1	-3.6	-3.7%	99.8	49.4	-15.9	-13.6%	1,520	38.1	-9.8	-0.6%
1992	528.3	17.2	-25.5	-4.6%	88.7	32.3	-3.9	-4.2%	92.8	46.6	-15.0	-13.9%	1,523	35.3	-7.1	-0.5%
1993	521.6	19.8	-26.5	-4.8%	84.4	31.7	-4.2	-4.7%	86.6	44.2	-14.2	-14.1%	1,528	32.8	-5.6	-0.4%
1994	517.6	21.8	-27.5	-5.0%	78.6	30.9	-4.6	-5.5%	79.5	41.7	-13.7	-14.7%	1,532	29.7	-3.5	-0.2%
1995	511.8	24.1	-28.5	-5.3%	74.8	30.1	-5.1	-6.4%	72.3	39.1	-13.1	-15.4%	1,534	26.5	-1.3	-0.1%
1996	509.8	26.0	-29.4	-5.5%	70.8	29.5	-5.6	-7.3%	66.2	37.0	-12.7	-16.1%	1,540	23.8	0.6	0.0%
1997	510.7	27.8	-30.4	-5.6%	67.6	29.1	-6.0	-8.2%	61.2	35.3	-12.4	-16.9%	1,552	21.5	2.2	0.1%
1998	513.4	29.5	-31.4	-5.8%	65.1	28.9	-6.4	-9.0%	57.1	34.1	-12.2	-17.6%	1,567	19.7	3.8	0.2%
1999	517.0	31.1	-32.3	-5.9%	63.1	28.8	-6.8	-9.7%	53.6	33.0	-12.0	-18.4%	1,585	18.1	4.9	0.3%
2000	522.0	32.6	-33.2	-6.0%	61.5	28.8	-7.1	-10.4%	50.8	32.2	-12.0	-19.1%	1,605	16.8	6.0	0.4%

RADIAN CORPORATION

TABLE A-2. EMISSIONS AND FUEL-CONSUMPTION MODEL RESULTS FOR SCENARIO 1A

CALENDAR YEAR	OXIDES OF NITROGEN (TPD) TOTAL EMISSIONS	EXCESS EMISSIONS	CHANGE FROM BASELINE	% CHANGE FROM BASELINE	UNBURNED HYDROCARBONS (TPD) TOTAL EMISSIONS	EXCESS EMISSIONS	CHANGE FROM BASELINE	% CHANGE FROM BASELINE	PARTICULATE MATTER (TPD) TOTAL EMISSIONS	EXCESS EMISSIONS	CHANGE FROM BASELINE	% CHANGE FROM BASELINE	FUEL CONSUMPTION (MM GAL/YR) TOTAL FUEL USE	EXCESS FUEL USE	CHANGE FROM BASELINE	% CHANGE FROM BASELINE
1985	487.7	4.4	-23.2	-4.5%	91.8	32.3	-3.0	-3.2%	99.5	48.8	-18.2	-15.4%	1,361	38.3	-11.5	-0.8%
1986	515.9	4.8	-23.7	-4.4%	99.1	34.9	-3.2	-3.1%	107.9	53.0	-19.2	-15.1%	1,457	41.0	-11.8	-0.8%
1987	519.0	4.9	-23.7	-4.4%	101.2	35.6	-3.3	-3.1%	110.9	54.5	-19.8	-15.2%	1,474	41.4	-12.0	-0.8%
1988	527.1	6.2	-24.6	-4.5%	100.3	35.1	-3.2	-3.1%	108.9	53.2	-19.4	-15.1%	1,485	40.9	-11.7	-0.8%
1989	536.7	7.7	-25.6	-4.6%	98.8	34.4	-3.2	-3.1%	105.9	51.5	-18.6	-14.9%	1,492	40.2	-11.4	-0.8%
1990	538.8	8.8	-26.4	-4.7%	97.5	33.8	-3.2	-3.1%	104.2	50.4	-17.9	-14.7%	1,501	39.7	-11.0	-0.7%
1991	534.0	11.0	-28.1	-5.0%	93.7	33.2	-3.5	-3.6%	98.6	48.2	-17.1	-14.8%	1,519	37.6	-9.2	-0.6%
1992	524.1	13.1	-29.6	-5.4%	88.7	32.4	-3.8	-4.1%	91.7	45.5	-16.1	-15.0%	1,523	35.1	-7.3	-0.5%
1993	517.0	15.0	-31.1	-5.7%	84.4	31.7	-4.2	-4.7%	85.5	43.1	-15.3	-15.2%	1,528	32.9	-5.5	-0.4%
1994	512.5	16.8	-32.8	-6.0%	79.5	30.8	-4.7	-5.6%	78.4	40.6	-14.8	-15.8%	1,533	30.2	-3.1	-0.2%
1995	506.3	18.6	-34.0	-6.3%	74.8	29.9	-5.3	-6.7%	71.2	38.0	-14.2	-16.6%	1,535	27.3	-0.5	0.0%
1996	503.9	20.2	-35.2	-6.5%	70.5	29.2	-5.9	-7.7%	65.1	35.9	-13.8	-17.5%	1,541	24.9	1.7	0.1%
1997	504.5	21.5	-36.7	-6.8%	67.3	28.7	-6.4	-8.6%	60.1	34.2	-13.5	-18.4%	1,553	23.0	3.8	0.2%
1998	506.8	22.9	-38.0	-7.0%	64.7	28.5	-6.8	-9.5%	56.0	32.9	-13.3	-19.2%	1,569	21.3	5.3	0.3%
1999	510.0	24.2	-39.2	-7.1%	62.8	28.3	-7.3	-10.4%	52.4	31.9	-13.2	-20.1%	1,587	20.0	6.8	0.4%
2000	514.8	25.3	-40.4	-7.3%	61.0	28.2	-7.8	-11.1%	49.6	31.1	-13.1	-20.9%	1,607	18.9	8.1	0.5%

TABLE A-3. EMISSIONS AND FUEL-CONSUMPTION MODEL RESULTS FOR SCENARIO 1B

	OXIDES OF NITROGEN (TPD)				UNBURNED HYDROCARBONS (TPD)				PARTICULATE MATTER (TPD)				FUEL CONSUMPTION (MM GAL/YR)			
CALENDAR YEAR	TOTAL EMISSIONS	EXCESS EMISSIONS	CHANGE FROM BASELINE	% CHANGE FROM BASELINE	TOTAL EMISSIONS	EXCESS EMISSIONS	CHANGE FROM BASELINE	% CHANGE FROM BASELINE	TOTAL EMISSIONS	EXCESS EMISSIONS	CHANGE FROM BASELINE	% CHANGE FROM BASELINE	TOTAL FUEL USE	EXCESS FUEL USE	CHANGE FROM BASELINE	% CHANGE FROM BASELINE
1985	490.4	7.1	-20.5	-4.0%	92.4	32.9	-2.4	-2.5%	101.9	51.2	-15.7	-13.4%	1,383	39.9	-9.8	-0.7%
1986	516.6	7.6	-20.9	-3.9%	98.8	35.6	-2.5	-2.5%	110.4	55.5	-16.6	-13.1%	1,458	42.7	-10.1	-0.7%
1987	521.7	7.6	-20.9	-3.9%	101.9	36.2	-2.6	-2.5%	113.6	57.1	-17.2	-13.2%	1,475	43.1	-10.3	-0.7%
1988	530.0	9.1	-21.7	-3.9%	101.0	35.8	-2.6	-2.5%	111.5	55.8	-16.8	-13.1%	1,486	42.6	-10.1	-0.7%
1989	539.8	10.9	-22.8	-4.0%	99.4	35.0	-2.5	-2.5%	108.4	54.0	-16.1	-12.9%	1,494	41.8	-9.8	-0.6%
1990	541.9	12.1	-23.1	-4.1%	98.2	34.4	-2.5	-2.5%	106.6	52.8	-15.6	-12.7%	1,502	41.2	-9.5	-0.6%
1991	537.7	14.8	-24.3	-4.3%	94.4	33.9	-2.8	-2.9%	101.0	50.5	-14.8	-12.8%	1,521	38.9	-8.0	-0.5%
1992	528.4	17.4	-25.4	-4.6%	89.4	33.0	-3.1	-3.4%	93.9	47.7	-13.9	-12.9%	1,523	36.0	-6.4	-0.4%
1993	521.8	19.8	-26.3	-4.8%	85.1	32.4	-3.5	-3.9%	87.6	45.2	-13.2	-13.1%	1,528	33.6	-4.9	-0.3%
1994	517.7	22.0	-27.4	-5.0%	80.3	31.6	-3.9	-4.7%	80.5	42.7	-12.7	-13.6%	1,533	30.4	-2.9	-0.2%
1995	511.9	24.2	-28.4	-5.3%	75.5	30.8	-4.4	-5.5%	73.2	40.0	-12.2	-14.3%	1,534	27.0	-0.8	-0.1%
1996	509.9	26.2	-29.2	-5.4%	71.5	30.2	-4.9	-6.4%	67.1	37.9	-11.8	-15.0%	1,541	24.3	1.1	0.1%
1997	510.8	27.9	-30.3	-5.6%	68.3	29.8	-5.3	-7.2%	62.0	36.2	-11.6	-15.7%	1,552	22.0	2.7	0.2%
1998	513.5	29.6	-31.3	-5.7%	65.8	29.6	-5.7	-8.0%	57.9	34.9	-11.4	-16.4%	1,567	20.1	4.1	0.3%
1999	517.1	31.2	-32.2	-5.9%	63.7	29.4	-6.1	-8.7%	54.4	33.8	-11.3	-17.2%	1,585	18.5	5.3	0.3%
2000	522.2	32.7	-33.1	-6.0%	62.2	29.4	-6.4	-9.4%	51.6	33.0	-11.2	-17.8%	1,605	17.1	6.4	0.4%

TABLE A-4. EMISSIONS AND FUEL-CONSUMPTION MODEL RESULTS FOR SCENARIO 1C

CALENDAR YEAR	OXIDES OF NITROGEN (TPD) TOTAL EMISSIONS	EXCESS EMISSIONS	CHANGE FROM BASELINE	% CHANGE FROM BASELINE	UNBURNED HYDROCARBONS (TPD) TOTAL EMISSIONS	EXCESS EMISSIONS	CHANGE FROM BASELINE	% CHANGE FROM BASELINE	PARTICULATE MATTER (TPD) TOTAL EMISSIONS	EXCESS EMISSIONS	CHANGE FROM BASELINE	% CHANGE FROM BASELINE	FUEL CONSUMPTION (MM GAL/YR) TOTAL FUEL USE	EXCESS FUEL USE	CHANGE FROM BASELINE	% CHANGE FROM BASELINE
1985	490.1	8.9	-20.7	-4.1%	89.7	30.2	-5.1	-5.4%	99.4	48.7	-18.3	-15.5%	1,381	38.4	-11.4	-0.8%
1986	518.3	7.4	-21.2	-3.9%	96.9	32.6	-5.4	-5.3%	107.8	52.9	-19.3	-15.2%	1,457	41.1	-11.7	-0.8%
1987	521.5	7.4	-21.2	-3.9%	98.9	33.3	-5.6	-5.3%	110.8	54.4	-20.0	-15.3%	1,474	41.5	-12.0	-0.8%
1988	529.8	8.8	-22.0	-4.0%	98.0	32.8	-5.5	-5.3%	108.8	53.1	-19.5	-15.2%	1,485	40.9	-11.7	-0.8%
1989	539.5	10.5	-23.0	-4.1%	98.5	32.1	-5.5	-5.3%	105.8	51.3	-18.7	-15.1%	1,492	40.2	-11.4	-0.8%
1990	541.8	11.7	-23.5	-4.2%	95.3	31.6	-5.4	-5.3%	104.0	50.2	-18.1	-14.8%	1,501	39.8	-11.1	-0.7%
1991	537.4	14.4	-24.7	-4.4%	91.8	31.1	-5.6	-5.7%	98.4	48.0	-17.3	-15.0%	1,519	37.3	-9.6	-0.6%
1992	528.1	17.1	-25.7	-4.6%	86.8	30.4	-5.7	-6.2%	91.5	45.3	-16.3	-15.1%	1,522	34.5	-7.8	-0.5%
1993	521.5	19.4	-26.7	-4.9%	82.6	29.9	-6.0	-6.7%	85.3	42.9	-15.5	-15.4%	1,527	32.1	-6.3	-0.4%
1994	517.4	21.7	-27.7	-5.1%	77.9	29.2	-6.3	-7.5%	78.3	40.5	-14.9	-16.0%	1,532	29.1	-4.2	-0.3%
1995	511.8	23.9	-28.7	-5.3%	73.2	28.5	-6.7	-8.4%	71.1	37.9	-14.3	-16.7%	1,533	25.9	-1.9	-0.1%
1996	509.8	25.8	-29.6	-5.5%	69.2	27.9	-7.1	-9.3%	65.1	35.9	-13.8	-17.5%	1,540	23.3	0.0	0.0%
1997	510.5	27.6	-30.6	-5.7%	66.1	27.6	-7.5	-10.2%	60.1	34.2	-13.5	-18.4%	1,551	21.1	1.7	0.1%
1998	513.2	29.3	-31.6	-5.8%	63.7	27.4	-7.8	-11.0%	56.0	33.0	-13.3	-19.2%	1,567	19.2	3.2	0.2%
1999	518.8	30.9	-32.5	-5.9%	61.6	27.4	-8.2	-11.7%	52.5	32.0	-13.1	-20.0%	1,584	17.7	4.5	0.3%
2000	521.9	32.4	-33.4	-6.0%	60.1	27.4	-8.5	-12.4%	49.7	31.2	-13.0	-20.7%	1,605	16.4	5.7	0.4%