California Environmental Protection Agency

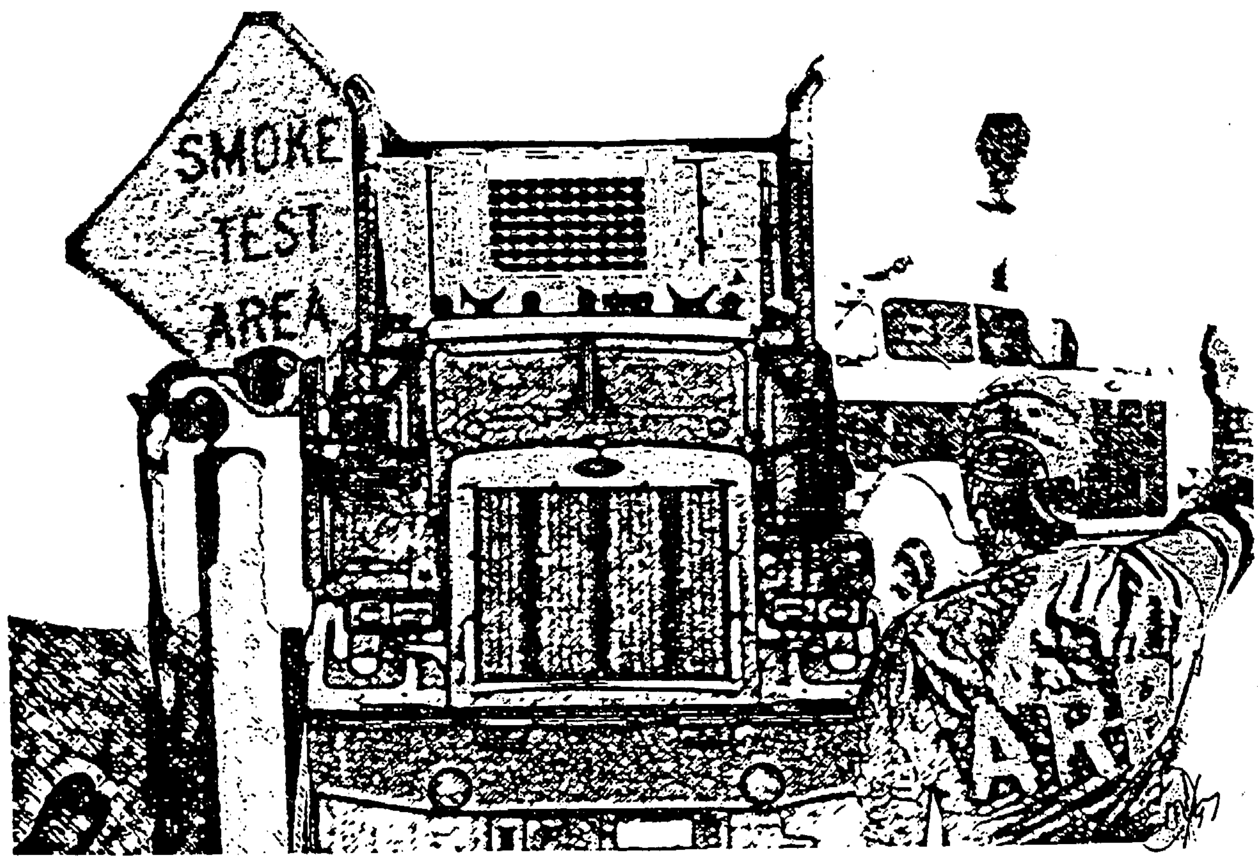
Air Resources Board

Technical Support Document for the
Proposed Amendments to the California Regulations Governing the:

HEAVY-DUTY VEHICLE INSPECTION PROGRAM

PERIODIC SMOKE INSPECTION PROGRAM

October 1997



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REGULATORY AMENDMENTS TO CALIFORNIA'S HEAVY-DUTY VEHICLE INSPECTION PROGRAM AND PERIODIC SMOKE INSPECTION PROGRAM

TECHNICAL SUPPORT DOCUMENT

Prepared by:

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October 1997

ACKNOWLEDGMENTS

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EXECUTIVE SUMMARY

1. BACKGROUND

Emissions from heavy-duty diesel vehicles are a major contributor to the total California inventory of particulate matter[1] (particulates, PM) and oxides of nitrogen (NO_x) emissions. These emissions pose significant environmental and public health impacts. Losses in agricultural productivity are estimated by the California Air Resources Board (ARB) and the University of California at $300 million to $1 billion per year. Public health impacts associated with diesel emissions include an increased chance of contracting various respiratory diseases and cancer. Additionally, excessive smoke emitted from heavy-duty vehicles continues to be the public's primary air pollution complaint.

In response to the above concerns, California Senate Bill (SB) 1997 was enacted in 1988 authorizing the ARB to implement a roadside smoke enforcement program designed to curtail the excessive smoke emissions resulting from malmaintained and tampered heavy-duty vehicles. Following a detailed field study, the ARB implemented the resultant program, the "Heavy-Duty Vehicle Inspection Program" (HDVIP), in November 1991. Additionally, a companion "Periodic Smoke Inspection Program" (PSIP) requiring California fleet owners to self-inspect their fleets for excessive smoke emissions was developed in 1993 in accordance with California SB 2330. Although the HDVIP has been effective in reducing the number of excessively-smoking heavy-duty vehicles, its smoke test procedure (the "snap-acceleration" test) has been the focus of controversy. The trucking industry has argued that the HDVIP's snap-acceleration test is unreliable and incorrectly fails clean trucks. This debate has been ongoing since the program's inception in 1991, and has now been litigated four times. In all cases, the test has been upheld by the California courts, including two decisions of the Third District Court of Appeals that were left standing by the California Supreme Court.

The HDVIP was suspended by the ARB in October 1993 to redirect staff to investigate reformulated diesel fuel performance issues. Around the same time, Assembly Bill (AB) 584 was enacted to address the concerns from the trucking industry. This legislation required that the test procedure used in the HDVIP produce "consistent and repeatable" results and stated this requirement would be satisfied through the adoption of a roadside smoke test procedure that was being developed by the Society of Automotive Engineers (SAE J1667). The legislation further required the test procedure to not produce false failures unless provisions were enacted to remedy them without penalty to the vehicle owner. Both the HDVIP and the PSIP are currently being conducted on a voluntary basis.

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[1] Particulate matter is generally classified as "PM-10", or particles with diameters of 10 microns or less, and "PM-2.5", that, similarly, consists of particles with diameters of 2.5 microns or less. Studies show that diesel exhaust primarily consists of PM-2.5.

2. PROGRAM REDIRECTION

In order to satisfy the twin objectives of adopting the SAE J1667 procedure and ensuring that any redirected enforcement program be consistent with the requirements of AB 584, the ARB conducted two field studies during the fall of 1996 and winter/spring of 1997. First, the "Random Truck Opacity Survey" served to quantify the smoke opacity distribution of heavy-duty diesel vehicles in conjunction with the SAE J1667 smoke test method. With this survey, the extent of the problem caused by malmaintained heavy-duty vehicles and the potential failure rate under a redirected HDVIP was quantified.

In the second study, the "Truck Repair Study", a sample of in-use trucks with different smoke levels were recruited and their engine malperformances (if any) were diagnosed and repaired. The intent of the Truck Repair Study was to develop appropriate smoke opacity standards based on the SAE J1667 test procedure that conformed to the legislative intent of AB 584. A brief overview of the SAE J1667 test procedure, the Random Truck Opacity Survey and Truck Repair Study follows.

SAE J1667

A key element of the smoke inspection test procedure for heavy-duty diesel vehicles is the method employed to measure smoke opacity. Historically, the SAE J1243 procedure recommended test guidelines that served as the basis to measure smoke opacity and were employed by the HDVIP. Since during a "snap-acceleration" test the emitted smoke can be a relatively short puff, the measurement response time of the smokemeter can have a major effect on the measured "peak" smoke emissions. The most significant difference between the new SAE J1667 procedure and the previous HDVIP test procedure (based on SAE J1243) concerns this issue. The SAE J1667 procedure more closely specifies the response time of the smokemeter.

Random Truck Opacity Survey

Between August and November of 1996, the ARB conducted a random roadside smoke testing survey (referred to as the Random Truck Opacity Survey[2]). The survey was used to profile the distribution of the in-use smoke opacities representative of the California fleet. In particular, it served to quantify the extent of the problem caused by malmaintained heavy-duty vehicles and the potential failure rate under a redirected HDVIP. A total sample of 1002 heavy-duty diesel vehicles representing all model year engine groups of interest (i.e., pre-1980, 1980-83, 1984-87, 1988-90, 1991+) was used in the analysis. A more detailed analysis of the Random Truck Opacity Survey is contained in Chapter 3 of this report.

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[2] Although formally known as the Random Truck Opacity Survey, the test program measured smoke emissions from all types of in-use heavy-duty diesel vehicles operating on California roadways, including buses.

Truck Repair Study

At the conclusion of the random survey, the ARB conducted a "Truck Repair Study" to gauge the effectiveness of repairing engines to manufacturers' specifications in lowering snap-acceleration smoke emissions. In all, 71 vehicles representing various engine model year makes with varying smoke opacity levels were recruited. All repairs were conducted at factory-authorized repair facilities.

In order to determine whether any false failures would result through the imposition of a particular standard, it is ideal to have a sample with as wide a representation of different engine designs (characterized by make, model year and model year designation) as possible. Given temporal and budgetary restraints, this study concentrated on those engine types that were of most interest from an emissions standpoint.

Once the repair phase of the Truck Repair Study was completed, a distribution of post-repair smoke opacity levels was determined. Through this distribution, smoke opacity standards designed to not cause false failures were selected to meet the legislative requirements of AB 584.

3. ANALYSIS OF RESULTS OF THE TRUCK REPAIR STUDY

The 71 vehicles recruited for the Truck Repair Study included 63 pre-1991 model year vehicles and 8 vehicles from the 1991^{+}. Of the 63 vehicles in the first group, 3 were not fully repaired. The sample of 63 pre-1991 engines (including those that were not fully repaired) were well distributed over the opacity range for the initial field test opacity. As shown by the distribution below, the sample is almost evenly represented over the opacity range, except in the 75 to 85 percent opacity range. This implies that cutpoints may be selected in the 40 to 65 percent opacity range with reasonable sample representation.

Opacity Range	Sample %
35 to 45	15.87
>45 to 55	17.46
>55 to 65	15.87
>65 to 75	26.99
>75 to 85	4.76
>85	19.05

The selection of the pass/fail cutpoints for pre-1991 engines should ideally be based on the optimization of the errors of commission and omission (i.e., false failures or false passes, respectively), as noted in the previous TSD for the HDVIP. However, the new legislative language requires that the ARB develop procedures so that no engine will fail the smoke standards and procedures when the engine is in good operating condition and set to the manufacturer's specifications. Given the restrictive language of the legislation, the selection of standards is based on a zero error of commission rate.

The post-repair opacity distribution is as follows for pre-1991 vehicles:.

Opacity Range	Sample %
5 to 10	6.3
>10 to 15	23.8
>15 to 20	17.5
>20 to 25	15.9
>25 to 30	20.6
>30 to 35	6.3
>35 to 40	4.8
>40	4.8 (Not fully repaired)

As can be seen from this distribution, the majority of the engines were repaired to smoke levels below 30 opacity-points. The highest post-repair smoke opacity recorded for a fully-repaired engine was 38.7 percent.

The three trucks not fully repaired included: one that had been incorrectly rebuilt; a second with a very worn engine, as confirmed by excessive blowby; and a third where repairs completed did not bring the smoke opacity down as expected. In the last case, the mechanic suggested injector problems, but this could not be confirmed as the owner was unwilling to wait for further diagnostics and potential repair. This engine had a post-repair smoke opacity of 47 percent, while the very worn engine had a post-repair smoke opacity of 49.8 percent. Under a very conservative analysis, one could consider the engine with possible injector problems as the highest post-repair value for an engine in "good working order" since the problems remain unconfirmed. It could also be argued that the acceptance of the "worn" engine into the program indicates it may have been marginal and that its opacity could represent the best possible post-repair value for an engine that may be nearing the end of its useful life. However, the mechanic's confirmation of excessive blowby provided a strong case for excluding this vehicle from the sample.

A similar opacity distribution analysis is of more limited value for the sample of 1991^{+} engines because of the small sample of vehicles.

No.	Vehicle No.	Pre-Repair Opacity	Post-Repair Opacity
1	67	22.8	18.9
2	56	28.2	11.0
3	65	29.2	20.5
4	70	30.3	19.2
5	63	31.3	30.6
6	71	38.8	28.5
7	43	43.4	25.6
8	4	57.5	15.1

The post-repair smoke opacity of the small sample appears relatively high. For example, unlike the pre-1991 model year sample, no engines were repaired to below 10 percent opacity. In addition, two engines (on vehicle 63 and 67) showed negligible smoke opacity reduction after repair (i.e., the pre- and post-repair smoke opacities differed by less than 5 percent).

The repair records on the 1991^{+} engines indicate that some mechanics may be unfamiliar with electronic systems (see Chapter 5). The results of the small sample are at odds with the fact that most 1991^{+} vehicles have very low smoke emissions along certification peak smoke levels that are 50 to 70 percent below HDVIP standards for pre-1991 engines.

4. SELECTION OF STANDARDS

In response to the legislative intent of AB 584, the selected standards must be selected such that:

- none of the vehicles repaired to "good operating condition" will fail the standard;
- issues regarding variability in smoke measurement must be addressed to prevent false failures.

The first point was directly addressed using the post-repair opacity distributions. The second point was addressed by quantifying the assorted variabilities and factoring them into the cutpoint equations.

Cutpoints

For pre-1991 engines, a reasonable choice of the highest opacity after repair is 38.7 percent[3], indicating a possible range of standards above 39 percent opacity. However, the existence of one engine (repaired to 47 percent opacity) that had additional unconfirmed malperformances could suggest that a more conservative standard be applied. For 1991⁺ engines, the equivalent highest post-repair value is 30.6 percent, suggesting a possible range of standards above 31 percent.

Associated Variability

Another issue to be considered is the variability of measured smoke opacity. There are three types of variability: one associated with the engine itself; the second with test performance; and the third associated with variation among different meters certified to the SAE J1667 standard. The issue of engine variability is complex since it is dependent on the time period over which it is measured. Engines may become more variable with use and over time for reasons associated with deterioration of parts, or contamination by ambient dust or fuel impurities. A key factor in this analysis is that variability associated with detectable causes is not accounted for in the standard-setting process as its causes are associated with correctable malperformances.

The second source of variability is the short-term cycle-to-cycle variability of individual engines' opacities measured by the same meter. The variability of the meter's measurements of these opacities also contributes to this source. All other factors are assumed to be held constant. Data on this source of variability must be obtained from engines in good working order. The data are obtained from observed differences between the opacities of two tests performed within a relatively short time period during which in-use deterioration is very unlikely to have occurred.

Engines' cycle-to-cycle variability was estimated from pairs of post-repair smoke opacity tests in the TRS. The first test of the pair was performed by dealership staff and the second test by the ARB field staff. These pairs of measurements were performed on the same day or on successive days -- but more importantly, the engine was presumably operated very little between the two measurements. Data from pairs of tests is available for 25 of the 71 engines in the TRS sample. Differences of these paired measurements had a mean of 0.20 percent and a standard deviation of 1.92 percent.

Variability of the measurements of opacities of the same J1667 test by different meters satisfying the J1667 meter specifications, the third type of variability, was estimated from the results of a study of the correlation of five such meters conducted in April 1996. Pairs of smokemeters simultaneously measured the same smoke plumes of six representative engines. The standard deviation of these paired differences of these meters was 2.4 percent. The statistical

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3 This value was associated with the high post opacity observed for an engine that was fully repaired.

independence of these two sources of variability is very plausible, because they were measured in completely independent experiments. The standard deviation of the combined independent sources of variability is 3.1 percent

An allowance for the combined measurement variability of the second and third sources is computed as a one-sided upper tolerance interval for their sum. The computed tolerance interval covers 95 percent of the population and has a confidence level of 95 percent. Their coverage of a high proportion of the population at a high confidence level makes such intervals well-suited to estimating allowances for variability in situations where the number of false failures is to be minimized. Assuming that the two sources of variation are normally distributed, the computed tolerance interval is an allowance for variability of 7.2 percent, which is conservatively increased to 8 percent.

Using the reference post-repair high value of 47 percent for pre-1991 engines, and 30.6 percent for 1991^+ engines, the equivalent standards should be 55 percent and 40 percent, respectively, which are identical to the standards used in the previous HDVIP. However, in both cases, the post-repair high opacity values may not reflect complete or correct repairs and the standards may be too conservative. It appears possible and likely that a larger sample of data on repairs, especially on 1991^+ engines, could lead to a significantly lower standard than the 40 percent value derived in this analysis.

5. <u>TYPES OF REPAIR</u>

The data base from the Truck Repair Study included written comments by mechanics on the types of repair. These comments were the basis for dividing the repairs performed into specific categories. Unfortunately, mechanics' written repair comments were unclear in some cases so that the exact sequence of repairs along with the emissions benefits versus costs for incremental repairs could not be fully determined. As a result, the analysis focused on the "endpoint" of all repairs. The repair sample is based on data from all 71 trucks recruited, even though three trucks were not fully repaired for reasons previously discussed. The sample has good representation of the heavy-heavy-duty diesels makes.

High smoke emissions are normally due to:

- Improper transient air/fuel ratio control;
- Problems with the fuel injection system or fuel injection timing;
- Inadequate intake air.

Of these, transient air/fuel ratio control maladjustment is largely responsible for high smoke during the snap-acceleration test.

All of the transient air/fuel ratio controls are applicable only to turbocharged diesel engines, but all engines in the sample are turbocharged. In the repaired sample, 70 percent of engines (50) had defects in this part of the system. In addition, this rate was very similar across different manufacturers' engines and very similar to the rate observed in the repair sample developed by ARB when designing the HDVIP in 1989-90.

A large percentage of the other repairs were also associated with the remaining fuel control system. These included adjusting the governor, setting the fuel rack position and setting the injection timing to specification - all necessary adjustments on diesel engines. The impact of governor tampering on smoke opacity is engine-model dependent, but governor tampering is relatively common on Cummins engines. The metering pump was rebuilt or replaced for a large fraction of the sample. Finally, injectors (or injection nozzles) were repaired or replaced in over one-third of the engines (20) in the sample.

Most of the 1991$^+$ engines featured electronic control of injection timing as did a few 1988-1990 engines. In particular, the DDC Series 60 engines in the sample were all electronically controlled, and every Series 60 engine in the sample was given an electronic control-module program update. All electronically-controlled engines had their internal diagnostics queried, but no system faults were found. This may be because current diagnostic systems in heavy-duty diesel engines are not designed to recognize faults causing high smoke on the snap-acceleration test. There are also some concerns on the ability of this test to recognize malperformances in electronic systems.

The replacement of the air filter was another common repair performed in one-third of the sample. Turbochargers needed replacement on 4 of 71 turbocharged engines, but one was due to leaky oil seals, and was not repaired in this study. In addition, valves were adjusted on several engines, which is part of general tune-up but has limited impact on smoke opacity.

On average, all four engine model year groups showed significant reductions in smoke from repair. The pre-repair and post-repair average values are shown in the following table. The three vehicles that were not fully repaired are excluded.

	Average Pre-Repair Opacity	Average Post-Repair Opacity
Pre-1980 (15 vehicles)	65.9	22.4
1980-1987 (29 vehicles)	63.6	20.7
1988-1990 (16 vehicles)	56.0	17.3
1991$^+$ (8 vehicles)	35.0	21.2

Post-opacity levels were independent of pre-repair levels. However, as expected, trucks with the highest pre-repair opacities had the greatest levels of reductions. (It should also be noted that even the truck with the highest pre-repair opacity, after modest repairs, had a post-repair opacity well below the proposed cutpoints.)

The reductions in opacity obtained for 1991$^+$ vehicles were similar to those for pre-1991 vehicles, except in two instances where no meaningful reductions were obtained. Because of the small total sample size, no detailed analysis could be performed. The opacity was generally reduced to the 11 to 20 percent opacity range after repair in six vehicles that exclude the two with minimal post-repair smoke reduction. Hence, the expectation is that a larger sample and better repairs could indicate an average post-repair smoke opacity level of about 15 percent, independent of pre-repair levels. This expectation is also consistent with the fact that certification peak smoke levels for 1991$^+$ engines have declined 50 to 70 percent from pre-1991 certification levels.

The Truck Repair Study had operational cost ceilings of $750 for repairs in order to meet budgetary constraints. This amount included $500 provided by ARB, and a $250 supplement provided, as necessary, by the respective engine manufacturer. In some cases the manufacturer provided additional repair money. In a few instances the customer agreed to pay the amount not covered by ARB or the engine manufacturer. Other than the three engines for which repairs were incomplete, all other engines were repaired to levels determined to be adequate by the dealers without regard to cost. Most repairs included a base cost associated with diagnostics and dynamometer testing so that these costs alone, independent of repairs, added a total of $120 to $180 representing 1 to 2 hours of mechanic's time (typically @ $60/hr) plus a dynamometer fee of $60 to $70.

The average costs for the sample of 68 fully-repaired engines are as follows:

Pre-1980 (15 vehicles)	$732
1980-1987 (29 vehicles)	$565
1988-1990 (16 vehicles)	$827
1991$^+$ (8 vehicles)	$433
Overall average	$652

The reason why the pre-1980 and 1988-1990 vehicles exhibited higher average costs is because there were some relatively rare repairs that were expensive and that inflated the average cost. For the pre-1980 engines, two engines had their turbochargers replaced. In the 1988-1990 vehicle sample, one engine had an intercooler replaced and another had a new injection pump installed. The replacement parts increased costs by over $750 per engine, but the 1980-1987 sample did not have any similar repairs. A more realistic representation is to average the costs across the four model year strata to obtain a mean value of $652.

The 8 engines in the 1991+ group had average repair costs of only $433. This figure is lower than those for previous years largely because there were no major replacement part costs. This is due to the fact that the trucks are, on average, less than 5 years old, and the cost estimate may be quite reasonable for vehicles 2 to 6 years old (vehicles less than 2 years old are typically covered by the manufacturer's new engine warranty). However, as these trucks age, it is likely that average repair costs will increase due to the need to replace worn turbochargers, intercoolers, injection pumps and injectors.

6. COSTS OF THE HDVIP AND PSIP

The cost and benefit analysis of this TSD consider the effects of the overall HDVIP and PSIP with the proposed amendments compared to a baseline scenario where there are no heavy-duty vehicle inspection programs. Note that the Staff Report includes analyses of the inspection programs with the amendments proposed by the ARB staff, compared to the original programs as they now exist in the California Code of Regulations.

The HDVIP and PSIP impose certain costs on the regulated industry. These costs arise from a variety of program requirements and include: fleet costs for program administration; capital costs for vehicle inspections; costs for vehicle repair and indirect costs due to vehicle and driver out-of-service time. Fleet labor costs due to PSIP inspection requirements are estimated using heavy-duty diesel vehicle populations from the ARB's MVEI7G emissions inventory model and fleet size statistics from the U.S. Department of the Census. Capital costs for fleets are estimated based on equipment needs established during the original HDVIP and unit costs estimates derived from current market price data. A similar approach is taken to estimate demands for fleet equipment and associated costs under the PSIP.

Costs incurred due to vehicle repair require a more complex estimation methodology since the number of heavy-duty diesel vehicles requiring repair is directly dependent on the number of vehicles failed under the HDVIP and PSIP and the number of vehicles that undertake preventive maintenance to avoid HDVIP or PSIP failure. To estimate the number of heavy-duty diesel vehicles expected to fail the HDVIP and PSIP in the program evaluation years of 1999 and 2010, smoke opacity data developed during the Random Truck Opacity Survey was analyzed in conjunction with recommended program cutpoints. Based on this analysis, it is estimated that 13.1 percent of heavy-duty diesel vehicles will fail either an HDVIP or PSIP inspection in 1999 and 8.6 percent of such vehicles will fail an inspection in 2010. These estimates, combined with total vehicle populations from the MVEI7G emissions inventory model and per-vehicle repair costs, yield estimates of the total cost of failure-driven vehicle repair.

Some vehicle owners will elect to undertake voluntary repairs to avoid the risk of HDVIP and PSIP inspection failure. The costs of these deterrence-based vehicle repairs were estimated using data collected under the original HDVIP, and MVEI7G data on the heavy-duty diesel vehicle population. During the original HDVIP, the observed failure rate declined from 44.7 percent immediately following program implementation to 18.5 percent just prior to program suspension. Basic analysis of this data indicates that approximately 26 percent of all heavy-duty diesel vehicles were subjected to some level of improved maintenance in response to HDVIP implementation. This statistic compares favorably with the 33 percent estimate developed prior to implementation of the original HDVIP. Applying this fraction to total heavy-duty diesel vehicle populations and the average costs of repair yields an estimate for the total cost of deterrence-induced repairs resulting from implementation of the HDVIP and PSIP.

Indirect costs due to the implementation of the HDVIP and PSIP result from lost vehicle and driver time due to vehicle inspection and repair. These lost-opportunity costs have been estimated using statistics for the heavy-duty diesel vehicle population, the HDVIP and PSIP inspection, failure and repair rates, and estimates of the average time required to undertake inspections and repair vehicles.

Finally, vehicle owners will recoup a cost savings due to repair-induced reductions in vehicle fuel consumption. Estimates of fuel savings in 1999 and 2010 were derived using a detailed malperformance and vehicle repair model (also used to estimate repair-induced vehicle emissions impacts). Based on this model, a net reduction in heavy-duty diesel vehicle fuel consumption of 0.69 percent is expected in 1999 and 0.66 percent in 2010. An estimate of total cost savings resulting from these reductions was developed by applying the percentage-change estimates in fuel consumption to total heavy-duty diesel fuel consumption statistics from the MVEI7G model and per-gallon fuel costs. Table ES-1 presents a summary of estimated HDVIP and PSIP program costs.

7. <u>BENEFITS OF THE HDVIP AND PSIP</u>

As with the cost analysis, the emissions impact analysis in this report evaluates the impact of the overall inspection programs compared to having no such programs. The Staff Report also includes an incremental analysis showing the impact of the programs with the proposed amendments incorporated, compared to the originally-adopted programs.

TABLE ES-1

HDVIP AND PSIP COSTS

	1999	2010
Total Annual Administrative Cost to Fleets	$16,986,121	$22,487,646
Annual Repair Cost	$21,162,379	$16,229,616
Annual Increased Maintenance Cost	$2,267,097	$2,947,141
Annual Lost Opportunity Cost of Time	$771,936	$567,603
Annual Cost of Fuel	($21,764,145)	($24,983,116)
Total Program Cost	$19,423,388	$17,248,890

The overall HDVIP and PSIP produce a series of benefits that can be generally classified as follows:

- A reduction in the number of heavy-duty diesel vehicles emitting excessive smoke;
- A reduction in criteria and toxic air pollutant emissions from heavy-duty diesel vehicles;
- A reduction in heavy-duty diesel vehicle fuel consumption;
- A potential improvement in heavy-duty diesel vehicle reliability and performance.

Reducing the number of heavy-duty diesel vehicles emitting excessive smoke is the primary goal of the HDVIP and PSIP. Reductions in criteria pollutants (i.e., hydrocarbons or "ROG", NO_X and PM) and toxic air contaminants, reductions in fuel consumption and any improvements in vehicle reliability and performance accrue as direct, but secondary, benefits of the smoke reduction repairs.

The reduction in the number of heavy-duty diesel vehicles emitting excessive smoke due to HDVIP and PSIP implementation was estimated using data collected during the original HDVIP. During that program, the observed failure rate declined from 44.7 percent immediately following program implementation to 18.5 percent just prior to program suspension. This change in vehicle failure rate can be directly converted to an estimate of the number of vehicles for which excessive smoke emissions have been eliminated. However, based on the Random Truck Opacity Survey, some of the improvement observed during the original HDVIP has eroded and, therefore, implementation of the proposed HDVIP and PSIP can be expected to induce renewed vehicle maintenance practices in response to the threat of citation.

Based on the assumption that vehicle maintenance practices will equilibrate at the levels observed during the original HDVIP, the proposed amendments will reduce the number of excessively-smoking heavy-duty vehicles operating in California by approximately 29,000 in 1999 and by 38,000 in 2010. This equates to reducing the number of excessively-smoking vehicles from California's roadways from 1999 through 2010 by approximately 625,000 due to the combined effects of the HDVIP and PSIP amendments.

HDVIP- and PSIP-induced repairs will also bring about a reduction in emissions of ROG, NO_x and particulates. Using a detailed engine malperformance model in conjunction with the MVEI7G emissions inventory model, Statewide emission reduction impacts (in tons per day) have been estimated as follows:

	ROG	NO_x	PM
1999	6.37	12.24	5.24
2010	5.30	14.03	3.19

As indicated in the cost discussion, this same malperformance model was used to estimate changes in the volume of heavy-duty diesel fuel consumed due to HDVIP and PSIP implementation. The estimated reduction in heavy-duty diesel fuel consumption of 0.69 percent in 1999 and 0.66 percent in 2010 translates to a savings of 16.7 million gallons of diesel fuel annually in 1999 and 19.2 million gallons of diesel fuel annually in 2010, or approximately 250 million gallons over the 12-year period. This represents a savings of over $212 million based on current diesel fuel prices.

Implementation of the HDVIP and PSIP is also expected to cause reductions in the total mass of toxic emissions emitted by heavy-duty diesel vehicles and potentially improve heavy-duty diesel vehicle reliability and performance. However, due to the lack of definitive analysis tools for assessing the magnitude of these benefits, no quantitative estimate of program benefits in these areas has been developed.

8. HDVIP AND PSIP COST EFFECTIVENESS

The primary cost effectiveness of the HDVIP and PSIP cannot be estimated conventionally in terms of dollars per mass of pollution reduced. The primary focus of the HDVIP and PSIP is to reduce smoke emissions, a reduction that cannot be meaningfully addressed in terms of emissions mass. Instead, as described above, primary program benefits were estimated in terms of a reduction of excessive smoke from 70,000 heavy-duty diesel vehicles operating in California.

As a secondary benefit, the HDVIP and PSIP also produce reductions in criteria pollutant emissions as a result of repairs performed to reduce excess smoke. These associated criteria pollutant impacts can be combined with program costs to derive a cost effectiveness estimate in units of dollars per pound of emission reduction. However, this cost effectiveness estimate only considers the secondary benefits of the HDVIP and PSIP.

Based on the estimated program costs and criteria pollutant emission reductions presented above, the cost effectiveness of the secondary benefits of the HDVIP and PSIP is estimated to be $1.12 per pound in 1999 and $1.05 per pound in 2010. These estimates compare favorably to alternative emission control programs that primarily target criteria pollutant reductions and typically cost between $2.50 and $5.00 per pound of emissions reduced.

CHAPTER 1

INTRODUCTION

Emissions from heavy-duty diesel vehicles are major contributors to the total California inventory of particulate matter[1] (particulates, PM) and oxides of nitrogen (NO_x) emissions. These emissions pose potentially serious environmental and public health impacts. Losses in agricultural productivity from environmental impacts are estimated by the Air Resources Board (ARB) at $300 million to $1 billion per year. Public health impacts include increased rates of respiratory diseases and cancer. Additionally, excessive black smoke from heavy-duty vehicles continues to be the primary target of public complaints regarding air pollution.

In response to the above concerns, California Senate Bill (SB) 1997 was enacted in 1988, authorizing ARB to design and implement a Heavy-Duty Vehicle Inspection Program (HDVIP). Following a detailed field study for the design of an effective program, the ARB implemented the HDVIP in November 1991. The study results were presented to the Board in 1990 in a Technical Support Document (henceforth referred to as the "1990 TSD".) In addition, a companion Periodic Smoke Inspection Program (PSIP) requiring an annual self-inspection for California fleet vehicles was instituted in 1993 in accordance with California SB 2330. While the HDVIP and PSIP were very successful in reducing the number of smoky trucks, the test procedure used (the "snap-acceleration" test) was the focus of much controversy. The trucking industry has argued that the HDVIP's snap-acceleration test is unreliable and incorrectly fails clean trucks. This debate has been ongoing since the program's inception in 1991, and has now been litigated four times. In all cases, the test has been upheld by the California courts, including two decisions of the Third District Court of Appeals that were left standing by the California Supreme Court.

The HDVIP was suspended by the ARB in October 1993 to redirect staff to investigate reformulated diesel fuel performance issues. During the 1993/94 California legislative session, Assembly Bill (AB) 584 was enacted to address the concerns from the trucking industry. It was required in AB 584 that the test procedure used in the HDVIP produce "consistent and repeatable" results and that this would be satisfied through the adoption of a roadside smoke test procedure that was being developed by the Society of Automotive Engineers (SAE J1667). The legislation further required the test procedure to produce no false failures unless provisions were enacted to remedy them without penalty to the vehicle owner. Both the HDVIP and the PSIP are currently being conducted on a voluntary basis.

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[1]Particulate matter is generally classified as "PM-10", or particles with diameters of 10 microns or less, and "PM-2.5", that, similarly, consists of particles with diameters of 2.5 microns or less. Studies show that diesel exhaust primarily consists of PM-2.5.

In response to the new SAE J1667 test and AB 584, the ARB sponsored another study to evaluate new pass/fail standards for the HDVIP using the SAE J1667 procedure that will meet the legislative requirements regarding false failures. Under the new legislative guidelines, false failures are defined as "the failure of a vehicle to meet the standards adopted, when the vehicle is in good operating condition and is adjusted to manufacturers specifications." In the ARB Truck Repair Study conducted in the first half of 1997, a wide range of heavy-duty vehicles with different smoke opacities were recruited and repaired to manufacturer specifications by authorized dealerships and repair facilities. The results of this repair study are utilized to develop smoke opacity standards for the HDVIP and PSIP amendments that conform to the legislative requirements. The results of the study are documented in this Technical Support Document (TSD), that supports staff's proposal for regulatory amendments to the HDVIP and PSIP.

Chapter 2 of this TSD provides an overview and background on the previous HDVIP and PSIP, including their legal bases and actual implementation. Chapter 3 discusses the program redirection as a result of new requirements, and the studies conducted by ARB to support the regulatory amendments. Chapter 4 details the development of standards for the proposed amendments to the HDVIP and PSIP regulations. Chapter 5 addresses truck repairs and repair costs incurred in the truck repair study. Chapter 6 estimates total HDVIP costs and builds from the 1990 TSD, as most of the administrative and operational procedures of the HDVIP are proposed to continue unchanged. Chapter 7 estimates program emission benefits and Chapter 8 discusses program cost-effectiveness.

CHAPTER 2

BACKGROUND OF THE HDVIP AND PSIP

2.1 OVERVIEW

Although heavy-duty diesel vehicles have been significant contributors to the overall national emissions inventory of NO_x and PM, interest in controlling their in-use emissions has grown only during the last decade. This is due in part to the perception that diesel emissions do not increase significantly with the age and use of the engine, and in part because test methods and standards to implement a diesel inspection and maintenance (I/M) program have not been established by EPA. In spite of these facts, there have been several programs to mitigate smoke emissions from in-use heavy-duty diesel vehicles since the 1970's. Arizona was the first to implement such a program in 1970, and four other states have active programs in effect today. Other states have had regulations on their books, but have not (as of yet) had an active enforcement program.

California's HDVIP was operational between November 1991 and October 1993. In contrast to other states' programs, the HDVIP was preceded by extensive study of appropriate test procedures and pass/fail criteria required to implement a successful I/M program. A detailed survey of other states with heavy-duty diesel inspection programs revealed that actual failure rates in some programs were unrealistically low (1 to 3 percent of all heavy-duty diesel vehicles tested.) In contrast, the HDVIP recorded substantially higher failure rates (in the range of 30 percent.) During the two years that the HDVIP was being actively enforced, the percentage of smoky trucks showed a significant decline, confirming the program's effectiveness.

2.2 LEGAL BASIS FOR THE CALIFORNIA HDVIP

California has led the nation in imposing aggressive emission standards for new motor vehicles, and has viewed emissions of in-use heavy-duty diesel vehicles with increasing concern. Analysis showed that this category of heavy-duty vehicles contributed to 30 percent of the statewide NO_x emissions and 75 percent of the PM emissions from on-highway motor vehicles. Moreover, smoky trucks and buses continue to be the number-one source of complaints from the public regarding air pollution.

In response to potential environmental and public health impacts from heavy-duty diesel vehicle emissions, California SB 1997 (Presley, Chapter 1544, Statutes of 1988) was enacted authorizing the ARB to design and enforce the HDVIP. The HDVIP was first implemented on November 25, 1991. This program was designed to significantly reduce excess emissions from heavy-duty vehicles that result from poor maintenance and/or tampering. International (due to the implementation of NAFTA), interstate, and intrastate heavy-duty trucks and buses are subject to this program.

The primary goal of the HDVIP is to cite excessively-smoking heavy-duty diesel vehicles operating in California, and the program largely achieved these goals. The HDVIP was designed to be a roadside inspection program. Unlike registration-based inspection programs, the HDVIP targets all heavy-duty diesel vehicles traveling on California's roads, making in-state, out-of-state and out-of-country heavy-duty diesel vehicles equally likely to undergo inspection. Consequently, California trucks are not at a competitive disadvantage. The test procedure used was called the "snap-idle test" (now known as "snap-acceleration") and smoke measurement methods were based on the prescribed SAE J1243 procedure. In October 1993, the ARB temporarily suspended enforcement of the HDVIP and redirected staff efforts to other issues.

In concert with the HDVIP, the PSIP was mandated by California SB 2330 (Killea, Chapter 1455, Statutes of 1990) in an effort to promote self-enforcement by fleet owners of the smoke opacity standards of fleets. Under the PSIP, California-based fleets with two or more heavy-duty diesel vehicles are required to conduct annual smoke opacity and tampering self-inspections. The ARB is required to audit these fleets by reviewing their maintenance and inspection records. In addition, the ARB was required to test a representative sample of heavy-duty diesel vehicles to ensure program compliance, using the test procedures and standards identical to those specified in the HDVIP. Since the PSIP relied on the HDVIP regulations, it too is currently not enforced by ARB. In the interim, staff has encouraged fleet owners to voluntarily follow existing program guidelines.

2.3 HDVIP/PSIP ENFORCEMENT

During the spring of 1989 and until November 25, 1991, the ARB staff conducted pilot and pre-enforcement programs to both develop the formal enforcement program and gain voluntary industry compliance prior to HDVIP implementation. At the conclusion of the pre-enforcement program, the failure rate was 34 percent, considerably lower than the failure rate during the pilot programs. The enforcement phase of the HDVIP was implemented on November 25, 1991. During the two years of enforcement, the failure rate continued to drop to 18.5 percent in 1993 (see Table 2-1). This corresponds to a 35 percent reduction in the failure rate resulting in annual reductions of NO_x and PM emissions of 19 tons per day (4 percent) and 32 tons per day (39 percent), respectively, at a cost-effectiveness of $0.44 and $0.47 per pound, respectively (compared to $2.30 per pound for the current Smog Check program.) It should be noted that the vast majority of trucks cited had smoke opacity of over 85 percent, as shown in Figure 2-1.

Vehicles were tested at California Highway Patrol (CHP) inspections facilities and weigh-stations statewide, as well as at random roadside locations. The test included a snap-acceleration stationary vehicle test utilizing an electronic smokemeter and an inspection of the engine and emissions control system for tampering. The owners of vehicles failing the prescribed test procedures were issued citations that required the expeditious repair of the vehicle and carried civil penalties ranging from $300 to $1800 per violation. Failure to clear citations could result in the vehicle being removed from service by the CHP (Health and Safety Code section 44011.6(I) and Vehicle Code section 27159). Vehicle owners could appeal citations through the ARB's Administrative Hearing Program (Health and Safety Code section 44011.6(m) and Title 17, California Code of Regulations, section 60075.1).

To date, HDVIP civil penalty assessments exceed $2.6 million and collections exceed $2.0 million (see Table 2-1). These funds are deposited into the Vehicle Inspection and Repair Fund (VIRF) and Diesel Emission Reduction Fund (DERF). The VIRF monies are used to support the HDVIP and the Smog Check Program. The DERF monies are used to support clean diesel fuels and technology research, as mandated by AB 1107 (Moore, Chapter 940, Statutes of 1989).

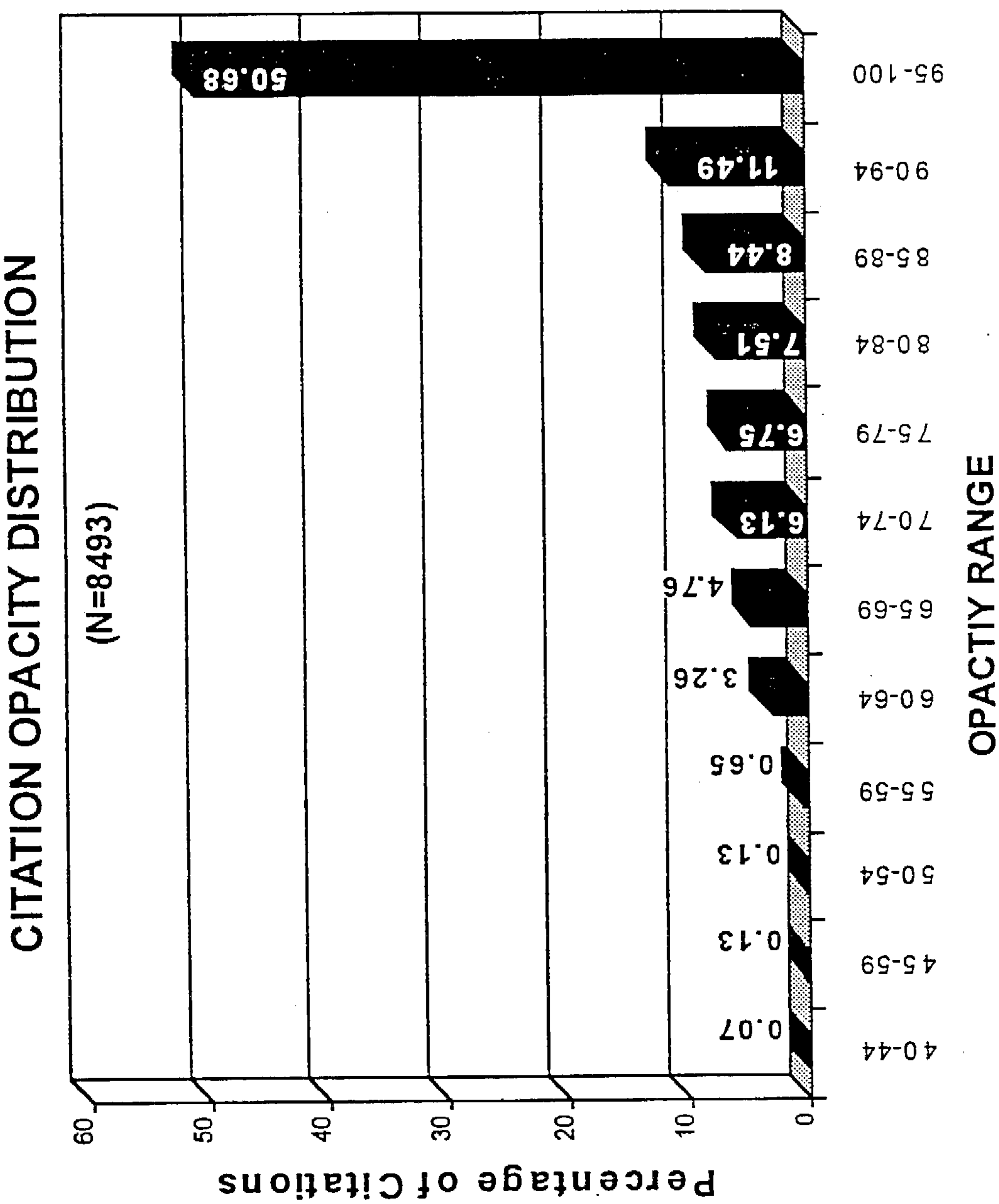
Table 2-1
Heavy-Duty Diesel Vehicle Inspection Program Enforcement Statistics
November 25, 1991 through October 15, 1993

Year	1991	1992	1993	Totals
No. Of Inspections	857	18,239	19,851	38,947
No. Of Citations	383	4,431	3,679	8,493
Failure Rate	44.7%	24.3%	18.5%	21.8%
No. Cleared	20	2,716	3,620	6,356 (75%)
No. Appealed	3	487	*669	1,159
Penalties Assessed	114,900	1,341,700	1,156,700	2,613,300
Penalties Collected	9,300	856,598	1,209,102	2,075,000 (79.4%)

* 667 in 1993; 2 in 1994.

Source: ARB Mobile Source Operations Division, HDVIP Status Reports

Figure 2-1



CITATION OPACITY DISTRIBUTION
(N=8493)
Percentage of Citations
0
10
20
30
40
50
60
OPACTIY RANGE
40-44
45-59
50-54
55-59
60-64
65-69
70-74
75-79
80-84
85-89
90-94
95-100
0.07
0.13
0.13
0.65
3.26
4.76
6.13
6.75
7.51
8.44
11.49
50.68

CHAPTER 3

REDIRECTION OF THE HDVIP

3.1 SAE J1667 BACKGROUND

In response to the concerns surrounding the SAE J1243 smoke test procedure, the SAE formed a task group in 1991 to develop an amended procedure (SAE J1667) that would address the issues at hand. This task group included representatives from the ARB, EPA, diesel engine manufacturers, smokemeter manufacturers, the trucking industry and from other interested parties. After a multi-year process by the task group, the final SAE J1667 procedure was issued in February 1996[1].

In order to satisfy the twin objectives of adopting the SAE J1667 procedure and ensuring that any redirected program would be consistent with the requirements of AB 584, the ARB conducted two field studies. The first was called the Random Truck Opacity Survey. As the name implies, heavy-duty diesel vehicles were randomly sampled from the fleet and tested using the new SAE J1667 procedure. The purpose of this survey was to obtain an in-depth understanding of the smoke opacity distribution of the California fleet, so that both the extent of the smoky truck problem and the potential failure rate under a redirected HDVIP (using the SAE J1667 procedure) could be quantified. The second study was the Truck Repair Study, where a sample of in-use trucks with high smoke opacity could be recruited and have their engine malperformances (if any) diagnosed and corrected through repair. The purpose of the Truck Repair Study was to develop standards for smoke opacity using the SAE J1667 test that conformed to the requirements of AB 584.

This chapter provides a brief summary of the new SAE J1667 procedure, focusing on the differences between the new procedure and the procedure previously employed by the HDVIP. This chapter also provides an overview of the two studies conducted by the ARB, the results of which are utilized in the following sections of this TSD.

3.2 THE SAE J1667 PROCEDURE

A key element of the inspection procedure for smoke emissions from heavy-duty diesel vehicles is the method of smoke measurement used. Historically, the SAE J1243 procedure was the basis for the smoke measurement method, and this method was applicable to any specific test cycle employed. During the snap-acceleration test, smoke emissions can be emitted as a relatively

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[1] SAE J1667/1, relating to equivalency between different manufacturer's smokemeters is still pending. Completion is expected by the end of 1997.

short-duration puff of smoke, and the response time of the instrument used to measure the opacity of the puff affects the measured value of peak smoke opacity. The most significant difference between the SAE J1667 procedure and the procedure employed previously by ARB is in the instrument response time specifications.

The SAE J1667 is described is detail in Appendix A and incorporates:

- A specific method for performing the snap-acceleration test;
- Correction factors for normalizing measured smoke opacity when measurements are made at alternative optical path lengths and non-standard ambient conditions;
- Specifications for the smokemeter, and especially for overall instrument response time.

The snap-acceleration test implementation defined in SAE J1667 is almost identical to the procedure ARB used previously in the HDVIP. Minor modifications include revisions to the time span spent at governed speed and specifications limiting the amount of idle between successive snap-acceleration cycles. The SAE J1667 procedure requires that the throttle be held at the fully-open position until the time the engine reaches governed speed, plus an additional 1 to 4 seconds. Upon releasing the throttle, the operator must allow the engine to remain at low idle for at least 5 seconds, but not more than 45 seconds, before initiating the next snap-acceleration cycle. These particular time requirements were absent in the previous ARB specification. The SAE J1667 procedure also requires at least three rather than two preconditioning cycles required previously by ARB.

Correction factors have been specified for optical path length variations, and for ambient conditions. The optical path length corrections would be applicable to non-standard exhaust stack diameters (defined as 5 inches for engines in the 301 HP to 500 HP range, and as 4 inches for engines in the 201 to 300 HP range). Due to the relative rarity of non-standard exhaust sizes and operational difficulties in determining stack diameter, this correction has not been normally employed in the field. The ambient correction factors were derived for snap-acceleration peak smoke measured for a sample of trucks at various altitudes, and uses a reference dry air density of 1.1567 kg/m^3. The SAE J1667 procedure requires that this correction be included for altitudes greater than 1500 ft above sea level, and for ambient temperatures over 80 °F.

The smokemeter specifications in SAE J1667 allow the use of either partial flow or full flow smokemeters, and smoke measurement in either opacity or density scales. The SAE J1667 procedure suggests the use of a green Light-Emitting Diode for the light source in the smokemeter. It also specifies a reduced zero drift rate of ±1 percent opacity per hour, half the previous ARB specification. However, the most significant difference is the use of an electrical filter to adjust total instrument response time to 0.500 ± 0.010 seconds. The SAE J1667 procedure requires a second-order digital Bessel filter, and defines instrument response time as:

$$t = SQRT\ (t_p^2 + t_e^2 + t_f^2)$$

where: t_p is the physical response time of the instrument sampling train
t_e is the electrical system response time
t_f is the filter response time

In a full flow end-of-line smokemeter such as the one used historically by ARB, t_p and t_e are much smaller than 0.5 seconds. In such cases almost all of the averaging is achieved by the Bessel filter. Historically, ARB has used a low-pass filter and strip chart recorder to act as averaging devices, but the response times for these devices can be different from those recommended in SAE J1667.

An SAE J1667 sub-committee is examining a correlation procedure for SAE J1667-compliant meters, and this sub-committee had conducted a series of tests on several meters in early 1996. The sub-committee's stated purpose is to assess the correlation of smokemeters that ostensibly meet SAE J1667 specifications based on real world testing, and regulatory agencies are required to establish pass/fail criteria for correlation testing. The procedure is to be described in an Appendix to the SAE J1667 document, but is not yet formally complete. Since ARB has already acquired and tested SAE J1667-compliant smokemeters, this appendix will not directly impact any of the results discussed in this TSD.

3.3 THE RANDOM TRUCK OPACITY SURVEY

Between August and November of 1996, the ARB conducted a random roadside smoke testing program for heavy-duty diesel vehicles. This test program, formally known as the Random Truck Opacity Survey[2], included the application of the SAE J1667 snap-acceleration smoke test procedure to randomly-selected heavy-duty diesel vehicles in an effort to develop a profile of heavy-duty diesel vehicle smoke characteristics for the California fleet. Through this study, SAE J1667 smoke test results were obtained for a usable sample of 1002 vehicles. (As described in Section 5.4.2, testing results for 190 vehicles were unusable due to incomplete or erroneous data.) Table 3-1 presents a breakdown of the sample by test location and by model year group. The Random Truck Opacity Survey provided a detailed characterization of the smoke opacity distribution of heavy-duty diesel vehicles for all model year groups of interest to this TSD.

All smoke testing performed under the Random Truck Opacity Survey was conducted in strict accordance with SAE J1667 procedures. As specified under the SAE J1667 test procedure, data other than actual smoke test results are needed in order to make a standardized

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[2]Although formally known as the Random Truck Opacity Survey, the test program measured smoke emissions from all types of in-use heavy-duty diesel vehicles operating on California roadways, including buses.

determination of emitted smoke, since both smoke production rates and smoke measurements can be dependent on test conditions. Smoke production rates, which are sensitive to combustion air/fuel ratios, can vary with meteorological conditions affecting air density. Even under identical meteorological conditions, smoke measurement, which relies on a determination of the degree of light absorption and scattering, is sensitive to the distance the transmitted light must pass between its source and a detector (this distance is known as the optical path length). Because of this dependency, two engines with identical smoke generation rates and different diameter exhaust stacks will generate different opacity readings (using full flow end-of-line smokemeters). The SAE J1667 test procedure includes corrections to address both phenomena and produce standardized smoke measurements. Data required to perform the necessary SAE J1667 smoke measurement corrections include the effective optical path length to correct for different exhaust stack sizes, and meteorological parameters to correct for differences in ambient air density. For full flow end-of-line type smokemeters, the effective optical path length is generally equivalent to exhaust stack diameter. For partial flow sampling smokemeters, the effective optical path length for smoke measurement is a function of the meter's internal sampling chamber. However, partial flow sampling smokemeters require the user to input the stack diameter for the test vehicle and actual smoke measurements are internally corrected to this input "path length" prior to reporting. As a result, both end-of-line and partial flow smokemeters report smoke measurements based on the stack diameter of the test vehicle. To correct for differences in ambient air density, parameters such as dry and wet bulb temperatures and barometric pressure must be measured at the time of testing.

The Random Truck Opacity Survey included collection of all such required data as well as additional data to classify the subject test vehicle and engine population according to gross vehicle weight rating, class and model year. These data were used, after data cleaning and applying the optical path and ambient corrections, to develop estimates of future failure rates.

3.4 TRUCK REPAIR STUDY

The requirement in AB 584 to prevent false failures is based on the concept that an engine in good operating condition and set to manufacturer's specifications should meet applicable standards. Since the components of in-use engines are subject to wear and deterioration, deriving a precise definition of an engine in "good operating condition" is difficult. Even if such a definition were available, it would be time-consuming and expensive to check if all components in any given engine meet this definition. From an emissions perspective, ARB has previously identified gross polluters in the fleet in an I/M program, and subjected these gross polluters to repair. Hence, ARB's focus is on engines where the emission control system is malperforming, which certainly implies that the engine is not in good operating condition.

TABLE 3-1
DISTRIBUTION OF RANDOM TRUCK OPACITY SURVEY TEST LOCATIONS

Test Location	Model Year Group					Total Tested	Percent Tested
	Pre-1980	1980-83	1984-87	1988-90	1991+		
Northern California Locations							
Antelope	15	8	29	16	30	98	9.8
Cordelia	10	6	19	15	24	74	7.4
Los Banos	0	3	9	2	7	21	2.1
Northern Total	25	17	57	33	61	193	19.3
Southern California Locations							
Cache Creek	0	0	0	0	5	5	0.5
Castaic	5	7	22	26	46	106	10.6
Desert Hills	5	7	12	9	18	51	5.1
Grapevine	0	5	15	7	14	41	4.1
Rainbow	16	17	44	34	70	181	18.1
San Onofre	29	35	96	61	120	341	34.0
Temecula	2	6	5	9	8	30	3.0
Winterhaven	4	7	11	11	21	54	5.4
Southern Total	61	84	205	157	302	809	80.7
All Locations							
Sample Total	86	101	262	190	363	1,002	100.0

In order to set a standard that relates "good operating condition" to the absence of malperformance in engines, two hypotheses were developed to test any selected smoke opacity standard. The hypotheses are:

1. Any vehicle whose measured smoke emissions on the SAE J1667 test exceeded standard, x, would have one or more malperformances in the engine or emission control system.

2. If the malperformance or malperformances are repaired and the engine's adjustable parameters are set to manufacturers' specifications, the measured smoke emissions on the SAE J1667 standard would be below the standard.

Such a standard, x, could be derived from data on a sample of engines whose measured smoke opacity on the SAE J1667 test spanned a wide range of opacities. If these engines were subsequently diagnosed for malperformances, and any detected malperformances repaired, the pre- and post-repair smoke opacity data serve as the basis for selecting a standard.

The ARB conducted the Truck Repair Study to determine the appropriate standard through procurement and repair of a sample of heavy-duty diesel vehicles that spanned a range of smoke opacities. The distribution of post-repair smoke opacity levels, as measured with the SAE J1667 procedure, is utilized to select a standard that would result in no false failures per the legislative requirement of AB 584. In order to determine whether any false failures would result through the imposition of a standard, it is ideal to have a sample with as wide a representation of different engine designs, (characterized by the make, model type and model year designation) as possible. However, resource and time constraints limited total repair sample size to 71 engines. This section describes the established protocol during the conduct of the study for the Truck Repair Study; deviations from this protocol are detailed in the next chapter.

3.4.1 Sample Design

The sample of trucks to be recruited was stratified by model year groups, where each group of model years are homogenous or approximately homogenous in terms of certification emission standard stringency. Emission standards for heavy-duty diesel vehicles in California are shown in Table 3-2. Although the numerical emission standards show variations in the 1980-1987 time frame, it is due to changes to the test procedure between 1984 and 1985. The limiting factor in emission stringency was NO_x, and the emissions standards over the entire period were relatively constant at 6 g/BHP-hr for NO_x as measured on the steady state test. As a result, all engines certified over the 1980-1987 period met standards of approximately equal stringency. Trucks older than model year 1980 were also considered as one group largely because they comprise a small and diminishing share of the total heavy-duty diesel truck population. (A survey indicated that pre-1980 vehicles account for 7 to 9 percent of the total heavy-duty vehicle population).

Hence, the sample was divided into four model year group categories: pre-1980, 1981-1987, 1988-1990 and 1991-1993. Vehicles newer than model year 1993 could not be recruited for the study partly because of the rarity of finding such new trucks having significant or excessive smoke opacity levels, and partly because many are still under factory warranty, limiting owner interest in participating in this program.

The intent was to represent as wide a range of makes and models as possible, within each model year group. Engines were further stratified into medium-heavy- and heavy-heavy-duty types as per certification definitions. In each of these sub-strata, four engine manufacturers account for over 90 percent of all sales. The manufacturers are Cummins, Caterpillar, Detroit Diesel and Mack in the heavy-heavy-duty segment and International (Navistar), Caterpillar, GM (until 1990) and Ford in the medium-heavy-duty segment. There are a limited number of other makes and models in each segment, but resource constraints prevented testing all possible designs. The sample was to be focused on the different models offered by the manufacturers named above.

The third dimension to the sample stratification is the range of opacities of the vehicles to be selected for repair. The HDVIP had originally used 55 percent as the standard for pre-1991 vehicles and 40 percent opacity as the standard for 1991 and later vehicles. These standards were relative to the smoke measurement method used earlier. Comparative testing of the same sample of trucks using the previous ARB method and SAE J1667 method revealed that, on average, the SAE J1667-measured opacity values were approximately 4 percent lower for pre-1991 vehicles and 12 to 13 percent lower for 1991^+ and later vehicles, relative to the smoke opacity measured using the previous ARB method. It should be noted that these comparisons between the two measurement methods were not used to select standards for the SAE J1667 procedure but simply to indicate an appropriate range for examination. Hence, the region of interest for setting standards was expected to lie in the 40 to 100 percent opacity range for pre-1991 vehicles and 25 to 100 percent opacity range for 1991^+ vehicles. The resultant sampling plan provided a detailed definition of the make/model/model year group/opacity range of the desired sample.

3.4.2 <u>Test Protocol Design</u>

A brief summary of the test protocol is provided here as a guide. The plan was to recruit and repair a sample of 100 heavy-duty diesel vehicles, subject to time and resource constraints of the project. It should be noted that the test protocol had to be relaxed during the study, and the differences between the established and actual protocol are discussed in Chapter 4.

<u>Vehicle Recruitment</u> was to be accomplished by ARB field staff employed at weigh stations and roadside locations. Vehicles potentially exceeding the smoke opacity levels set as minimum criteria (40 percent for pre-1991 vehicles and 25 percent for 1991^+ vehicles) were to be tested by ARB staff using the SAE J1667 procedure, based on voluntary driver cooperation. A vehicle

Table 3-2
CALIFORNIA EXHAUST EMISSION STANDARDS FOR HEAVY-DUTY DIESEL ENGINES
(grams per brake horsepower-hour)

Model Year*	Total Hydrocarbons	Non-Methane Hydrocarbons†	Carbon Monoxide	Oxides of Nitrogen	Oxides of HC + NO_x‡	Particulates
1973-74	--	--	40	--	16	--
1975-76	--	--	30	--	10	--
1977-79	-- 1.0	-- --	25 25	-- 7.5	5 --	-- --
1980-83	1.0 --	-- --	25 25	-- --	6.0 5.0	-- --
1984	0.5	--	25	--	4.5	--
1985-87	1.3	--	15.5	5.1	--	--
1988-89	1.3	--	15.5	6.0	--	0.6
1990	1.3	1.2	15.5	6.0	--	0.6
1991-93	1.3	1.2	15.5	5.0	--	0.25[4]
1994-47	1.3	1.2	15.5	5.0	--	0.1
1998-2003	1.3	1.2	15.5	4.0	--	0.1
2004+	--	0.5	15.5	2.0	2.5	0.1/0.05

* The steady-state procedure was used through 1984 and the transient procedure has been used since 1985.

† Manufacturers may choose to certify to the total HC or the non-methane HC standard.

‡ Manufacturer has the option of certifying to separate HC and NO_x standards or to a combined HC + NO_x standard in 1977-79.

owner/operator whose truck had a smoke opacity that exceeded the minimum criteria was to be provided a flyer offering free repairs if their vehicle met the sampling plan requirements. The vehicle owner/operator was to be provided a toll-free number to call the recruiting contractor.

A vehicle meeting the sampling plan requirements was to be directed to an authorized dealership repair facility following a detailed conversation between the owner and the recruiting contractor (in this case, Parsons Engineering-Science) to verify vehicle eligibility.

Vehicle Qualification was to be performed by Parsons Engineering-Science and the repair facility. The first phase in the process was to insure that the vehicle engine model, model year and measured smoke opacity met the criteria of the sampling plan, and to obtain information on the engine maintenance history. The second phase of the qualification procedure was to occur at the dealership and included the following steps:

- A safety check to ensure that the engine did not cause any legal risk;
- A tampering and wear check, where mechanics would inspect trucks to identify extensive tampering or very worn engines that were rebuild candidates. Such engines were not accepted for repair;
- A pre-repair opacity check to ensure that the measured opacity was not significantly different (±5 opacity points) than the measured opacity value at the time of initial recruitment.

A vehicle meeting all three criteria was to be repaired under the study plan. The owner of a vehicle that was rejected from the repair program was paid a cash incentive for participation.

Vehicle Repairs were conducted at selected authorized dealerships only. These dealership had fully-qualified mechanics. Through the auspices of the Engine Manufacturer's Association, all major heavy-duty engine manufacturers participated in this program by providing technical and monetary assistance to the dealers performing repairs. Prior to conducting repairs, the dealership mechanics received a briefing from the contractor and ARB staff on record-keeping requirements as well as the sequence of repairs to be conducted. The repair sequence recommended that mechanics institute the lowest-cost repairs first and progress to higher-cost repairs as a possible means to examining incremental cost-effectiveness of repairs. However, the recommended sequence was not intended to guide the mechanic to perform any repair outside manufacturer's recommendations or to recommend any setting of timing or other adjustable parameters outside manufacturers specifications. Mechanics could (optionally) perform SAE J1667 smoke opacity tests at interim repair stages, and were required to perform a final post-repair SAE J1667 opacity check. ARB personnel were to validate this final opacity retest by performing a SAE J1667 test prior to vehicle release to the owner.

A cost ceiling of $750 was set for repairs, and if estimated cost requirements were higher, the repair shop was required to obtain special authorization to proceed. On a case-by-case basis, both ARB and the engine respective manufacturer were to provide additional funding, if required, to complete repairs. The vehicle owner could also be solicited for funding beyond the additional initial contributions. Repair records were required to be as complete as possible. Special cases of expensive repairs were to be examined on an as-required basis for approval. This was necessary to maintain total repair costs incurred under the study cost ceiling. (See Section 5.4 for a full discussion of costs.)

When the Truck Repair Study was conducted, it became necessary to relax some of the vehicle qualification requirements due to difficulties in obtaining the required sample. These deviations from the study design and the results of the study are discussed in Chapter 4.

CHAPTER 4

DEVELOPMENT OF STANDARDS FOR THE HDVIP AND PSIP

4.1 STANDARD SETTING REQUIREMENTS

It is specified in AB 584 that the adoption of the SAE J1667 test procedure and measurement methods will satisfy its requirements for consistency and repeatable test results. However, AB 584 does not suggest or recommend pass/fail standards for smoke opacity, instead leaving this decision to the regulating agencies. AB 584 requires that no vehicles be failed incorrectly. The specific language of the legislation is as follows:

1. The smoke standards and procedures shall be designed to ensure that no engine will fail smoke test standards and procedures when the engine is in good operating condition and is adjusted to manufacturer's specifications.

2. In implementing this section, the state Board shall immediately adopt procedures that either ensure there will be no false failures, or that ensure that the state Board will remedy any false failures without any penalty to the vehicle owner.

Under the previous program conducted by California, pass/fail standards were set by reference to the Federal Smoke Test Procedure (40 CFR, Section 86-884) that is used to certify new engines to the EPA standards for smoke opacity. Smoke opacity measured on the snap-acceleration test was linked to smoke opacity measured on the "rolling-acceleration" test, which, in turn, was linked to smoke opacity measured on the acceleration phase of the Federal Smoke Test Procedure. This complex linkage was needed because no data was available for a sample of diesel engines tested on the Federal Smoke Test Procedure and on the snap-acceleration test. However, the linkage between these smoke opacities remains controversial. (Note that, the SAE J1667 procedure explicitly states that it is not intended to correlate to the Federal Smoke Test.)

As a result, a new frame of reference was developed for the SAE J1667 procedure that allows definition of what constitutes a "failure" to meet applicable standards. In this revised definition, the presence of any observable and correctable malperformance in the engine is used as a criterion to gauge whether a particular vehicle is passed or failed incorrectly. It should be noted that the criterion is not explicitly linked to the magnitude of the emissions effect of any specific malperformance, although most malperformances affecting an engines' smoke opacity on the snap-acceleration test will affect engine emissions on the Federal Test Procedure. (It may also be true that an engine with no observable or correctable malperformance can have emissions higher than the standards to which it is certified, but the magnitude of the increase in such cases is expected to be small.)

The malperformance-based criterion then leads to specific definitions for properly- and improperly-failed vehicles. For any specific smoke opacity standard established using the SAE J1667 procedure, an improperly-failed vehicle (or a false failure) is one whose smoke opacity exceeds the standard on the SAE J1667 procedure, but cannot be diagnosed to have malperformances that, when corrected, do not reduce smoke opacity enough to meet the standard. A correctly-failed vehicle, in contrast, can be repaired to meet the applicable smoke opacity standard after repairs.

The adoption of malperformance-based criteria then directly links compliance with standards to the ability to repair such vehicles to meet standards. The objectivity of such a criterion could then depend on (1) the competence of the mechanic performing the repair and (2) the ability to improperly adjust the engine calibration to such a degree that it meets the specified smoke standard on the SAE J1667 test but falls outside the range of allowable calibrations, as specified by the manufacturer, to meet other criteria such as durability and driveability. The first issue of mechanic competence is avoided by referring diagnosis and repairs to dealerships and factory-authorized personnel, at least in theory. The second issue of improper adjustment is avoided by placing the additional restriction that the engine must be within manufacturer specifications after repair, per the legislative intent.

4.2 TRUCK REPAIR STUDY IMPLEMENTATION

The actual Truck Repair Study, as implemented, departed from the established study parameters as summarized in Chapter 3 for two reasons. First, recruitment of vehicles for the study proved much more difficult than envisioned. Many engine makes/models in the required opacity ranges (per the sample design) could not be found, and hence, the original sampling plan was not strictly followed. Second, extensive delays in the approval of SAE J1667 by the SAE committee lead to delays in starting the study. Available resources permitted the recruitment and repair of 71 trucks. As a result of the difficulty in recruiting trucks, the sample contained very few medium-heavy-duty trucks. Vehicles were recruited in both Northern and Southern California, with each area using a different brand of SAE J1667 meter for testing.

The difficulty in truck recruitment also led to some relaxation of the vehicle qualification criteria as the study proposed. Initially, the test protocol required that dealership opacity measurement match the field test measurement within ± 5 opacity-points. However, it became apparent that this criterion was too restrictive. The scheduling of potential recruits for repairs at dealerships was a time-consuming process and often several weeks elapsed between the initial ARB field test and the test at the dealership location. Over this period of time, some vehicles had experienced further engine deterioration, and some owners had performed minor repairs (e.g. changing the air cleaner) so that the ±5 opacity-points match requirements could not be enforced. While this requirement was not met by several vehicles in the sample, the average for the initial field test and the acceptance test at the dealership were within the requirement, because the opacities were both higher and lower at the dealership, relative to the measured opacity at the field test.

Eight trucks were rejected at the dealership based on qualification criteria. Five of the eight were due to extreme engine wear, and only a full rebuild would have restored these engines to specifications. In three cases however, the measured opacity at the dealership was below the acceptance criteria of at least 40 percent opacity (for pre-1991 engines). One of these engines was not field tested, but the other two bear discussion.

Both the engines that displayed unusual field behavior were DDC 8V-71 engines that were relatively old (1974 and 1981 model years). Both engines tested at relatively high opacities in the field (73.5 percent and 59.3 percent) but were below 30 percent opacity when tested at the dealerships. ARB staff conducted follow-up reviews on these engines and were able to document excessive variability in measured smoke emissions after a few minutes of idle time between successive SAE J1667 measurements. Large changes in smoke opacity of over 20 percent are indicative of malfunctions in the throttle-delay system or other fuel system controls, since other 8V-71 engines did not display such behavior. However, in the absence of actual repair data, we cannot confirm the hypothesis of malfunctions in the throttle-delay system.

Dealership repairs were selected during the program design phase as it was believed that issues of problem diagnoses and repair effectiveness issues would be minimized. However, it was found that the quality of diagnostics and repair varied between dealerships during the course of this study. In the sample of 71 vehicles, 9 vehicles had to undergo more than one repair cycle, due to incorrect or incomplete diagnosis by the dealership. In addition, three vehicles were not adequately repaired: one because the owner was unwilling to wait for additional repairs; the second because a serious parts mismatch was discovered that would require very expensive repairs not covered by the budget; and the third because the engine would have required a rebuild. Hence, some results are presented based on the 68 repaired engines and others based on the entire 71-engine sample. A comprehensive listing of all vehicles in the study, and a summary of their repairs is included as Exhibit 4-1 at the end of this section.

Documentation of the actual repairs performed was not at the level expected, since some mechanics filled out the forms incompletely or not in fully-understandable ways. Nevertheless, attempts were made to reconstruct the details on repairs performed by contacting mechanics on the telephone when the data was incomplete. Hence, available data on repairs is reasonably complete, although diagnostic-related time and expenses are less well understood, as explained in Chapter 5. A final post-repair opacity measurement conducted by ARB staff is available for all vehicles in the sample, so that pre- and post-repair data on smoke opacity is comprehensive and complete. Post-repair smoke opacities for all three pre-1991 model year groups are at 20 ± 2 opacity-points, a finding that suggest that older (pre-1980) engines can meet smoke opacity standards of the same stringency as 1980 to 1990 engines. This finding of similar behavior is also consistent with the technological similarity of engines built during the 1974 to 1990 time frame, a period over which most engines had evolutionary, not revolutionary improvements. Analysis of failure rates by model year also suggest that all 1990 and earlier trucks can be modeled as one population, as detailed in Chapter 5.

4.3 ANALYSIS OF RESULTS

The sample of 63 pre-1991 engines (including those that were not repaired completely) were well-distributed over the opacity range for the initial field test opacity. As shown by the data below, the sample is almost evenly-represented over the opacity span, except in the >75 to 85 percent opacity range, so that cutpoints can be selected in the 40 to 65 percent opacity range with reasonable sample representation. The distribution of the pre-1991 engine sample by opacity range for pre-repair opacity is as follows:

Opacity Range	Sample %
35 to 45	15.87
>45 to 55	17.46
>55 to 65	15.87
>65 to 75	26.99
>75 to 85	4.76
>85	19.05

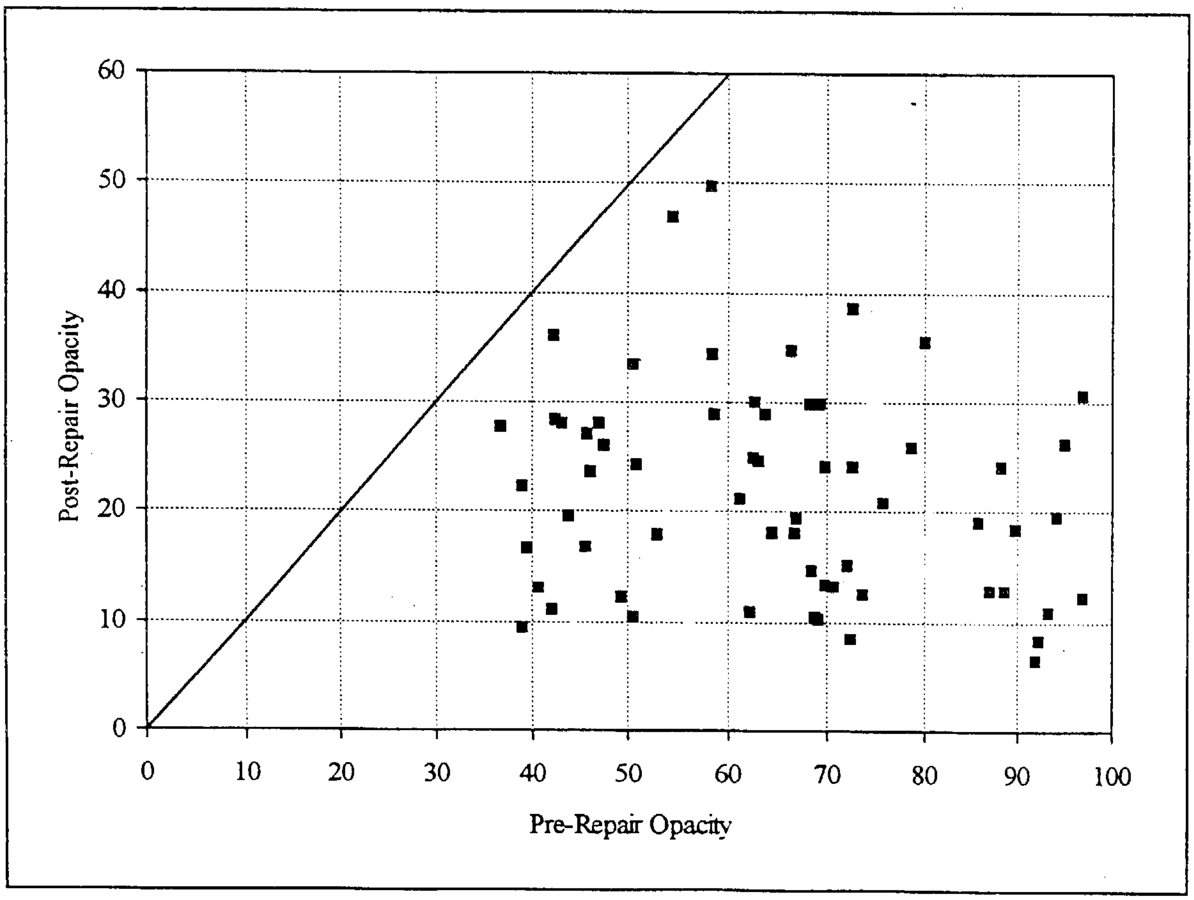
The selection of the pass/fail cutpoints for pre-1991 engines should ideally be based on the optimization of the false failures and false passes, as the 1990 TSD. However, the new legislative language requires that ARB develop procedures so that no engine will fail smoke standards and procedures when the engine is in good operating condition and set to manufacturers specification. Given the restrictive language of the legislation, selection of standards is based on a zero-false failure rate.

The post-repair smoke opacity is shown as a function of the pre-repair smoke opacity in Figure 4-1, for pre-1991 engines. Only the three incompletely repaired trucks have smoke opacity levels after repair over 40 percent. Post- repair smoke opacity is also clearly shown by Figure 4-1 to not be a function of pre-repair smoke opacity, i.e., the severity of the malperformance has no impact on how well the engine can be repaired.

The post-repair opacity distribution is as follows for pre-1991 vehicles:

Opacity Range	Sample %
5 to 10	6.3
>10 to 15	23.8
>15 to 20	17.5
>20 to 25	15.9
>25 to 30	20.6
>30 to 35	6.3
>35 to 40	4.8
>40	4.8 (Not fully repaired)

FIGURE 4-1



As can be seen from this distribution, the majority of the engines were repaired to smoke levels below 30 opacity points. The highest post-repair smoke opacity recorded for a fully-repaired engine was 38.7 percent.

The three trucks not fully repaired included: one that had been incorrectly rebuilt; a second with a very worn engine, as confirmed by excessive blowby; and a third where the repairs completed did not bring the smoke opacity down as expected. In the last case, the mechanic suggested injector problems, but this could not be confirmed as the owner was unwilling to wait for further diagnostics and potential repair. This engine had a post-repair smoke opacity of 47 percent, while the very worn engine had a post-repair smoke opacity of 49.8 percent. Under a very conservative analysis, one could consider the engine with possible injector problems as the highest post-repair value for an engine in good working order since the problems remain unconfirmed. One could also potentially argue that the acceptance of the "worn" engine into the program indicates it may have been marginal and its opacity could represent the best possible post-repair value for an engine that may be nearing the end of its useful life. However, the mechanic's confirmation of excessive blowby provides a strong case for excluding this vehicle from the sample.

A similar opacity distribution analysis is of more limited value for the sample of 1991⁺ engines. The sample consists of 8 vehicles, including two Isuzu NPR light-heavy-duty models (such engines have not been sampled in other model year groups). The pre-repair opacities in increasing order are as follows, as measured at the dealership:

No.	Vehicle No.	Opacity
1	67	22.8
2	56	28.2
3	65	29.2
4	70	30.3
5	63	31.3
6	71	38.8
7	43	43.4
8	4	57.5

Measurements at the dealership location rather the field location are listed for smoke opacity above, since not all vehicles had a field test in this sample.

It should be noted that pre-repair smoke opacities recorded in the field varied significantly (by more than 5 opacity percent) in two cases.

Post repair smoke opacity values were as follows:

No	Vehicle Number	Opacity
1	56	11.0
2	4	15.1
3	67	18.9
4	70	19.2
5	65	20.5
6	43	25.6
7	71	28.5
8	63	30.6

The post-repair smoke opacity of the small sample appears relatively high. For example, no engines were repaired to below 10 percent opacity unlike in the pre-1991 model year sample. In addition, two engines (on vehicles 63 and 67) showed virtually no smoke opacity reduction after repair, (i.e., the pre- and post-repair smoke opacities differed by less than 5 percent).

Indeed, the repair records on the 1991$^+$ engines indicate that some mechanics may be unfamiliar with electronic systems (see Chapter 5) The results of the small sample are at odds with the fact that most 1991$^+$ vehicles have very low smoke emissions, and certification peak smoke levels are 50 to 70 percent below certification peak smoke levels for pre-1991 engines.

4.4 SELECTION OF STANDARDS

In response to the legislative intent of AB 584, the selected standards must be such that:

- none of the vehicles repaired to good operating condition can fail the standard;
- issues regarding variability in smoke measurement must be addressed to prevent false failures.

The first point is directly addressed using the post-repair opacity distributions.

For pre-1991 engines, a reasonable choice of the highest opacity after repair is 38.7 percent, indicating a possible range of standards above 39 percent opacity. However, the existence of one engine (repaired to 47 percent opacity) that only had unconfirmed additional malperformances could suggest that a more conservative standard be applied. For 1991$^+$ engines, the equivalent highest post-repair value is 30.6 percent, suggesting a possible range of standards above 31 percent.

Another issue to be considered is one of variability of measured smoke opacity. There are three types of variability: one associated with the engine itself; the second with test performance; and the third associated with variation among different meters certified to the SAE J1667 standard. The issue of engine variability is complex since it is dependent on the time period over which it is measured. Engines may become more variable with use and over time for reasons associated with deterioration of parts, or contamination by ambient dust or fuel impurities. As an example, an engine may initially test at one value of snap-opacity, but may have a different value a few days later if the air cleaner is clogged from dust, or the vehicle is refueled with inadvertently-contaminated diesel. Over longer periods, the wear of engine components can increase smoke, but component failure can occur anytime with resulting increases in smoke emissions. Certain types of failures can also cause smoke opacity as measured on the SAE J1667 procedure to vary from test to test, making the measurement more variable. A key factor in this analysis is that variability associated with these causes are not accounted for in the standard-setting process as its causes are associated with correctable malperformances.

The second source of variability is the short-term cycle-to-cycle variability of individual engines' opacities measured by the same meter. The variability of the meter's measurements of these opacities also contributes to this source. All other factors are assumed to be held constant. Data on this source of variability must be obtained from engines in good working order. The data are obtained from observed differences between the opacities of two tests performed within a relatively short time period during which in-use deterioration is very unlikely to have occurred.

Engines' cycle-to-cycle variability was estimated from pairs of post-repair smoke opacity tests in the TRS. The first test of the pair was performed by dealership staff and the second test by the ARB field staff. These pairs of measurements were performed on the same day or on successive days -- but more importantly, the engine was presumably operated very little between the two measurements. Data from pairs of tests is available for 25 of the 71 engines in the TRS sample. Differences of these paired measurements had a mean of 0.20 percent and a standard deviation of 1.92 percent.

Variability of the measurements of opacities of the same J1667 test by different meters satisfying the J1667 meter specifications, the third type of variability, was estimated from the results of a study of the correlation of five such meters conducted in April 1996. Pairs of smokemeters simultaneously measured the same smoke plumes of six representative engines. The standard deviation of these paired differences of these meters was 2.4 percent. The statistical independence of these two sources of variability is very plausible, because they were measured in completely independent experiments. The standard deviation of the combined independent sources of variability is 3.1 percent

An allowance for the combined measurement variability of the second and third sources is computed as a one-sided upper tolerance interval for their sum. The computed tolerance interval covers 95 percent of the population and has a confidence level of 95 percent. Their coverage of a high proportion of the population at a high confidence level makes such intervals well-suited to estimating allowances for variability in situations where the number of false failures is to be minimized. Assuming that the two sources of variation are normally distributed, the computed tolerance interval is an allowance for variability of 7.2 percent, which is conservatively increased to 8 percent.

Using the reference post-repair high value of 47 percent for pre-1991 engines, and 30.6 percent for 1991$^+$ engines, the equivalent standards should be 55 percent and 40 percent respectively (which are identical to the standards used previously.) However, in both cases, the maximum post-repair opacity values may not reflect complete or correct repairs. It is possible that a larger sample of data on complete repairs could result in lower standards for both categories. Significantly lower standards for 1991$^+$ engines appear to be a distinct possibility.

Separately, it should be noted that this study sample of 71 heavy-duty vehicles obviously does not contain every possible make and model of heavy-duty diesel engine. Historically, ARB has relied on manufacturers to identify special engine certification families incapable of meeting the 55 percent or 40 percent standard, as applicable. These engine families were treated on a case-by-case basis, and ARB provided special exemptions from the standard to specific families, if justified. It is recommended that ARB continue this practice and re-examine the exempted list of families developed as a starting point to develop a new list of families exempted under the SAE J1667 procedure.

The current standards for opacities measured with SAE J1243 meters and the proposed standards for opacities measured with SAE J1667 meters have the same numerical values, but the proposed standards are in fact less stringent for almost all engines. This is due to the 0.5-second response-time requirement for SAE J1667 smokemeters that attenuates the peak opacities of sharply-peaked smoke profiles. Analysis of differences between opacities of the same engines measured by SAE J1243 and SAE J1667 meters a few minutes apart showed that the opacities measured with the latter were almost always smaller. For engines with electronically-controlled fuel systems, only 1 percent of the SAE J1667 opacities were larger. For engines with mechanically-controlled fuel systems, only 10 percent of the opacities were more than 3 opacity-points or larger. Some allowances should be made for the meters' measurements of non-identical smoke plumes. Hence, the proposed retention of the same numerical smoke standards of 40 percent and 55 percent will, in fact, provide an additional safeguard against false failures.

EXHIBIT 4-1

RESULTS OF TRUCKS THAT HAVE VISITED REPAIR FACILITIES
NORTHERN CALIFORNIA

Truck Repaired	Engine Make	Engine Model	Year	Field Test Date	Opacity	Repair Date	Location	Initial Opacity	Repairs	Cost	Final Opacity
2	Cummins	NTC 350	1986	1/09/97	85.8	3/4/97	Cummins-Sacramento	49.6 (air filter had been changed)	Fuel pump calibrated	$495.95	19.0
3	Caterpillar	3406-B	1986	2/10/97	70.7	3/5/97	Caterpillar - San Leandro	70.4	Air cleaner removal Pump setting adj Ratio control installed.	$812.37	67.7 62.1 13.2
6	Cummins	NTC 400	1984	2/25/97	52.8	3/17/97	Cummins-Sacramento	61.9	Pump recalibrated	$491.69	18.0
14	Mack	ETAZB6 73A	1978	2/20/97	94.1	4/21/97	Diesel Performance - Sacramento	82.6	Replaced puff limiter, exhaust manifold, and turbo	$1718.26 Owner paid overage	19.5
15	Cummins	NTC-400	1981	3/26/97	42.5	4/22/97	Cummins - San Leandro	40.6	Re-calibrated injectors	$748.68	28.4
20	IH	DT466	1982	3/19/97	43.1	4/17/97	Riverview Intl - Sacramento	51.8	Replaced injector	$369.61	54.7
						5/8/97	Dow Hammond - Modesto (fuel pump warranty work)		Rebuilt fuel pump	$0.00	28.0
23	Mack	EC6350	1988	5/6/97	63.8	5/16/97	Diesel Performance - Sacramento	74.4	Set overhead, replaced injector tips, replaced turbo cooler, adjusted aneroid	$1644.31 Owner to pay overage	28.8
24	Cummins	855	1982	5/19/97	69.8	5/21/97	Righetti - Stockton	89.7	Adjusted fuel pump Adjusted overhead and flushed injectors	$495.50	35.9 13.4
28	Caterpillar	1693	1974	4/8/97	68.8	5/22/97	Tenco Tractor - Sacramento	48.1	Rebuilt AFRC	$396.32	10.4
37	Cummins	L-10	1989	5/27/97	46.1	5/28/97	Righetti - Stockton	49.5	Replaced injectors	$860.55	23.6
42	Cummins	NTC 400	1984	5/24/97	96.9	5/29/97	Righetti - Stockton	96.3	Adj AFRC, flushed injectors	$966.00	32.3
43	Cummins	L-10	1993	5/27/97	22.2	5/30/97	Righetti - Stockton	43.4	Reset engine overhead and replaced 1 injector	$755.64	25.6
44	Cummins	855	1975	5/24/97	66.7	5/30/97	Righetti - Stockton	63.2	Adj AFRC Reset valves and injectors	$379.46	28.2 18.1

EXHIBIT 4-1

RESULTS OF TRUCKS THAT HAVE VISITED REPAIR FACILITIES
NORTHERN CALIFORNIA
(Continued)

Truck Repaired	Engine Make	Engine Model	Year	Field Test Date	Opacity	Repair Date	Location	Initial Opacity	Repairs	Cost	Final Opacity
45	Detroit	8V-71	1973	5/20/97	Fluctuated between 39 and 17	5/27/97	Delta Truck Center	33.0	Cleaned air filter	$245.96	26.2
						5/29/97			Tune-up (set valves, injectors, and governor)	$343.18	22.3
46	Cummins	NTC 400	1980	5/27/97	43.8	6/3/97	Righetti - Stockton	46.9	Adjusted fuel pump	$180.00	19.6
47	Cummins	NTC 350	1974	5/27/97	47.5	6/3/97	Righetti - Stockton	52.5	Installed new turbo charger	$922.12	26.0
48	Cummins	NTC 350	1984	5/28/97	69.3	6/4/97	Righetti - Stockton	82.4	Adjusted fuel pump	$183 being waived	32.2
						6/13/97		32.2	Replaced injectors	$776.83	29.8
49	Cummins	NTC 400	1989	5/28/97	45.7	6/4/97	Righetti - Stockton	40.7	Re-set overhead and replaced injectors	$777.38	27.1
50	Cummins	NTC 350	1988	5/20/97	45.5	6/4/97	Righetti - Stockton	45.6	Re-set overhead and replaced injectors	$777.38	16.8
51	Detroit	6L-71	1984	6/4/97	62.8	6/10/97	R&L - Stockton	61.6	Reset throttle delay Replaced rocker arms	$316.09	30.0
52	IH	DT466	1976	5/21/97	58.4	6/11/97	Interstate - Stockton	49.6	Replaced nozzles	$631.66	34.6
53	Detroit	6-71	1977	4/28/97	68.4	6/12/97	R&L - Stockton	73.7	Set throttle delay, replaced rocker arms, and tune-up	$548.68	14.6
54	Caterpillar	3406B	1987	5/28/97	39.6	6/13/97	Holt Bros - Stockton	37.2	Rebuilt AFRC	$283.12	16.7
55	Caterpillar	3406B	1987	5/28/97	36.8	6/13/97	Holt Bros - Stockton	38.9	Rebuilt AFRC	$480.38	27.7
56	Caterpillar	3176	1993	6/13/97	28.2	6/13/97	Holt Bros - Stockton	28.2	Timing and personality module	$414.19	9.5
57	Caterpillar	3306B	1984	5/28/97	58.6	6/13/97	Holt Bros - Stockton	55.1	Adjusted AFRC and replaced injector nozzles	$706.90	28.8
58	Detroit	6-71	1985	6/4/97	66.6	6/13/97	R&L Diesel - Stockton	75.7	Set throttle delay. Found mismatched injectors and liners	$408.79	68
59	Caterpillar	3176	1990	5/24/97	39	6/13/97	Holt Bros - Stockton	37.1	Set overhead		42.4
									Changed computer	$984.26	9.4
60	Detroit	8V-92	1977	6/2/97	95	6/16/97	R&L Diesel - Stockton	93.6	Installed throttle delay	$225.94	26.2

EXHIBIT 4-1

RESULTS OF TRUCKS THAT HAVE VISITED REPAIR FACILITIES
NORTHERN CALIFORNIA
(Continued)

Truck Repaired	Engine Make	Engine Model	Year	Field Test Date	Opacity	Repair Date	Location	Initial Opacity	Repairs	Cost	Final Opacity
63	Detroit	Series 60	1993	5/22/97	27.8	6/11/97	Interstate - Stockton	26.8	Checked computer code	$178.22	31.3
						6/18/97	Sierra DDC - Sacramento	31.3	Changed air filter and updated computer codes	$584.88	30.6
64	Detroit	Series 60	1990	5/28/97	50.4	6/5/97	Interstate - Stockton	60	Reset valves and injectors	$818.51	57
						6/18/97	Sierra DDC - Sacramento	54.9	Updated computer codes	$353.78	10.5
65	Detroit	Series 60	1992	5/28/97	37.5	6/19/97	Sierra DDC - Sacramento	29.2	Updated computer codes	$418.28	20.5
67	Detroit	Series 60	1992	5/28/97	27.8	6/25/97	Sierra DDC - Sacramento	22.3	Updated computer codes	$257.03	18.9
70	Isuzu	4BD2TC	1994	5/28/97	33.3	6/17/97	Suburban Ford - Sacramento	30.3	Adjusted valves	$472.78	30.5
71	Isuzu	4BD2TC	1994	5/27/97	31.2	6/27/97	Suburban Ford - Sacramento	38.8	Adjusted valves	$424.50	28.5

EXHIBIT 4-1

RESULTS OF TRUCKS THAT HAVE VISITED REPAIR FACILITIES SOUTHERN CALIFORNIA

Truck Repaired	Engine Make	Engine Model	Year	Field Test Date	Opacity	Repair Date	Location	Initial Opacity	Repairs	Cost	Final Opacity
1	Cummins	NTC 335	1971	12/19/96	62.5	2/7/97	Cummins - Rialto	94.8	New fuel pump installed	$800.00	24.9
4	Cummins	NTC 365	1990	2/18/97	72.1	3/5/97	Cummins - Rialto	57.5	Recalibrated fuel pump	$544.56	15.1
5	Cummins	NTC 400	1979	2/6/97	63.1	3/6/97	Cummins - Rialto	78.5	Recalibrated fuel pump	$469.99	24.6
7	Caterpillar	3406-B	1983	3/6/97	62.2	3/20/97	Caterpillar-Whittier	55.8	Changed air filter and gaskets AFRC reworked	$239.07 $243.85	55.3 11.0
8	Caterpillar	3406-B	1990	2/4/97	89.8	3/25/97	Caterpillar-Whittier	52.9	Changed diaphgram and reworked AFRC	$306.39	18.5
9	Cummins	NTC 400	1986	3/6/97	93.2	3/26/97	Cummins - Rialto	95.3	Repaired fuel pump	$539.10	10.9
10	Detroit	8V-92	1980	3/13/97	92.6	3/26/97	Detroit - City of Industry	92.0	Replaced injectors and throttle delay	$944.80	8.3
11	Cummins	NTC 400	1981	2/3/97	75.7	4/3/97	Cummins - Rialto	78.7	Recalibrated fuel pump	$525.85	20.8
12	Cummins	NTC 444	1988	3/17/97	54.5	4/10/97	Cummins - Rialto	58.0	Re-built Step Timing Control valve and oil leak at STC oil rail. Repair did not help much. Shops thinks that the truck may have bad injectors. Truck was released because truck owner said that he had to go.	$784.39	47.0
13	Caterpillar	3406-A	1981	3/17/97	96.9	4/16/97	Caterpillar-Whittier	98.0	Reconditioned AFRC	$353.28	12.2
16	Cummins	NTC 350	1985	4/9/97	46.9	4/23/97	Cummins - Rialto	41.0	Adjusted rail pressure and fuel linkage	$88.94	28.0
17	Cummins	NTC 350	1984	4/9/97	42.2	4/28/97	Cummins - Rialto	47.0	Recalibrated fuel pump. adjusted governor and AFRC	$496.57	11.1
18	Caterpillar	3306B	1988	3/31/97	73.9	4/30/97	Caterpillar-Whittier	92.4	Rebuilt and adjusted fuel ratio control	$348.28	6.6
19	Mack	EM6-300	1983	4/15/97	78.7	5/7/97	Mack - Anaheim	46.6 Difference between field and shop test is because truck owner had injectors cleaned and rebuilt.	Replaced reversing relay valve and adjusted injection pump	$357.91	25.9

EXHIBIT 4-1

RESULTS OF TRUCKS THAT HAVE VISITED REPAIR FACILITIES
SOUTHERN CALIFORNIA
(Continued)

Truck Repaired	Engine Make	Engine Model	Year	Field Test Date	Opacity	Repair Date	Location	Initial Opacity	Repairs	Cost	Final Opacity
21	Cummins	NTC-350	1988	2/18/97	61.2	5/14/97	Cummins - Montebello	40.9	Adjusted overhead	$472.83	21.2
22	Cummins	L-10	1988	3/19/97	59.8	5/15/97	Cummins - Rialto	92.9	Repaired and calibrated fuel pump	Owner to pay overage over $1,400	59.0
									Replaced all injectors and set valves	$1,956.46	13.1
25	Cummins	L-10	1984	5/19/97	49.7	5/19/97	Cummins - El Cajon	49.7	Adjusted fuel pump	Owner to pay overage	41.3
									Adjusted overhead and flushed injectors	$1,232.07	24.3
26	Caterpillar	3406B	1981	5/20/97	63.7	5/20/97	Power Systems - San Diego	88.3	Installed new air filter, repaired turbo leaks, tune-up (many settings were off)	$775.15	28.8
27	Cummins	L-10	1988	5/8/97	66.4	5/21/97	Cummins - El Cajon	82.0	Fuel Pump Calibration	$591.98	34.8
29	Cummins	NTC 350	1987	3/18/97	61	5/22/97	Cummins - Rialto	42.8	Adjusted AFRC	$247.71	18.1
30	Cummins	NTC	1989	3/5/97	80.1	5/22/97	Cummins - Rialto	91.3	Adjusted fuel pump and flush and tune	$941.71	62.3
						6/19/97	Cummins - Montebello	78.1	Adjusted fuel pump	$0.00	35.6
31	Caterpillar	3306 B	1975	5/8/97	50.5	5/22/97	Power Systems - San Diego	88.0	timing, fuel settings valves, air filter, nozzles	$1,039.20	33.4
32	Cummins	NTC 400	1979	5/8/97	72.6	5/22/97	Cummins - El Cajon	80.6	Adjusted fuel pump. Truck does have a bad cam shaft	$442.27	38.7
33	Cummins	L-10	1987	5/8/97	63.9	5/23/97	Cummins - El Cajon	76.0	Fuel Pump Calibration	$548.85	36.1
34	Mack	EC6-350	1988	5/8/97	68.2	5/20/97	E&W Equipment	51.4	Fixed plugged muffler, air cooler, and oil fill	$741.56	56.7
									Rebuilt fuel pump and injectors	$635.45 Owner to pay	29.8
35	Caterpillar	3306B	1986	5/8/97	66.9	5/23/97	Power Systems - San Diego	95.0	timing, fuel settings valves, air filter	$696.29	19.4

EXHIBIT 4-1

RESULTS OF TRUCKS THAT HAVE VISITED REPAIR FACILITIES
SOUTHERN CALIFORNIA
(Continued)

Truck Repaired	Engine Make	Engine Model	Year	Field Test Date	Opacity	Repair Date	Location	Initial Opacity	Repairs	Cost	Final Opacity
36	DDC	Series 60	1989	5/13/97	58.3	5/28/97	Valley DDC	Forgot to take initial test	Replaced 2 injectors and exhaust manifold	$1255.81 Owner to pay $200	49.8
38	Cummins	NTC 350	1984	4/1/97	87	5/27/97	Cummins - Montebello	96.0	Repaired fuel pump and installed missing AFRC parts	$793.19	12.8
39	Cummins	NTC 350	1979	4/3/97	88.6	5/28/97	Cummins - Montebello	89.0	Repaired fuel pump and installed missing AFRC parts	$906.73	12.9
40	Cummins	L-10	1987	5/23/97	72.6	5/29/97	Cummins - El Cajon	Did not have meter to take test	Repaired fuel pump	$544.34	47.4
						6/13/97		?	Flush and tune, replaced injectors	$959.98	27.9
41	Cummins	NTC 475	1985	5/21/97	88.2	5/27/97	Cummins - El Cajon	Did not have meter to take test	Repaired fuel pump	$759.94 rounded to $750 by Cummins	24.2
61	Detroit	6V-92	1979	5/27/97	69.1	6/10/97	Valley DDC - City of Industry	77.9	Replaced rocker arms and 1 injector	$755.65	70.7
						6/19/97	Harbor Diesel - Long Beach	67	Reset throttle delay Unplugged throttle delay orifice	$710.60	10.3
62	Caterpillar	3406B	1988	5/21/97	73.6	6/16/97	Power Systems - Whittier	81.3	Rebuilt AFRC	$176.26	12.5
66	Mack	EC6	1988	5/21/97	72.5	6/12/97	Mack -Anahiem	93.5	Repaired fuel pump	$1,962.38	8.4
68	Caterpillar	3406-B	1990	1/25/97	82.3	2/21/97	Caterpillar-Whittier		Reassembled AFRC valve that was sticking	$247.00	9.7
69	Caterpillar	3406-B	1986	5/23/97	49.2	6/20/97	Caterpillar - San Diego	?	Replaced nozzles	$805.93	12.3

CHAPTER 5

REPAIR TYPES AND COSTS

5.1 OVERVIEW

The analysis of repair types and associated costs is required for several reasons. First, the estimation of criteria pollutant emission reductions is through knowledge of the different engine malperformances and their individual or synergistic effects on emissions. The methodology to connect malperformance to emission increases was first developed by Radian (1988) and subsequently updated by Energy and Environmental Analysis in 1990. The types and rates of malperformances found in this repair study serve as validation for the malperformance model of emission benefits. Second, the average cost of repair has a significant bearing on program costs and cost effectiveness. Hence, costs derived in this section are utilized in the following sections of this TSD to derive program cost effectiveness. Third, repair costs have specific implications for the citation penalty structure. Since ARB plans to continue with the existing citation penalty structure, the repair costs are contrasted to the penalties to estimate their deterrence potential.

The analysis is described in three parts. First, the types of repair and their frequency of occurrence is analyzed. Second, the benefits of repair in terms of reduced peak smoke as measured on the snap-acceleration mode is derived from the data. Third, the cost of the various repairs and the implications for the citation penalty structure are discussed.

5.2 TYPES OF REPAIR

The database from the Truck Repair Study included written comments by mechanics on the types of repairs executed. These comments were the basis for dividing the repairs performed into a few specific categories. Unfortunately, mechanics' written comments on repairs were unclear in some cases, so that the exact sequence of repair, costs and benefits for less-than-complete repairs could not be fully determined. As a result, this analysis focuses on the endpoint of all repairs.

The repair sample is based on data from all 71 trucks recruited, even though three were not fully repaired for reasons previously discussed. Details of the types of trucks included in the repair sample is shown in Table 5-1. The sample has good representation of the heavy-heavy-duty diesels makes. The sample of vehicles in the medium-heavy-duty category was small, and a separate analysis would provide results of little significance. In addition, the types of repair for these engines are quite similar to those for heavy-heavy-duty engines. No light-heavy-duty diesels were included in the sample, since they are not normally found at weigh stations where the vehicles were recruited for this study.

High smoke emissions are normally due to:

- Improper transient air/fuel ratio control;
- Problems with the fuel injection system or fuel injection timing;
- In adequate intake air.

Of these, transient air/fuel ratio control maladjustment is largely responsible for high smoke during the snap-acceleration test. Each engine make has different designs that influence fuel injection system characteristics and adjustments to control transient air/fuel ratio. Cummins engines feature fuel injectors with a separate metering pump. Transient air/fuel ratio control is accomplished by modulating the metering pump line pressure under no-boost condition, referred to by mechanics as a "no-air pressure" adjustment. Control under turbocharger boost is accomplished by a plunger and bellows (or aneroid) mechanism. Most 1990 Caterpillar and Navistar engines feature a separate injection pump that provides both fuel metering and injection pressure. A separate mechanism, within the injection pump, also with a bellows, accomplishes transient air/fuel ratio control. Older two-stroke DDC engines and Mack engines are equipped with a throttle delay, or puff limiter, that essentially prevents high speed transient movements of the fuel rack in response to throttle movements. DDC engines have always featured unit injectors that include the metering mechanism and the high-pressure injection mechanism in a single unit. Unit injectors with electronic control of metering and injection timing are utilized in 1991^+ engines from several manufacturers. All of the transient air/fuel ratio controls are applicable only to turbocharged diesel engines, but all engines in the sample are turbocharged. As shown in Table 5-2, 70 percent of engines (50) in the repaired sample had defects in this part of the system. In addition, this rate was very similar across different manufacturers' engines, and very similar to the rate observed in the repair sample used in the 1990 TSD.

A large percentage of the other repairs were also associated with the rest of the fuel control system. These included adjusting the governor, fuel rack position or injection timing, which are necessary adjustments on all diesel engines. The impact of governor tampering on smoke opacity depends on the engine model, but governor tampering is relatively common on Cummins engines. The metering pump was rebuilt or replaced for a large fraction of the sample. Finally, injectors (or injection nozzles) were repaired or replaced in over one third of the engines (20) in the sample.

Most of the 1991^+ engines featured electronic control of injection timing as did a few of the 1988-1990 engines. In particular, the DDC Series 60 engines in the sample were all electronically controlled, and every Series 60 engine in the sample was given an electronic control module program update. It was not clear if this was necessary in all cases; in at least one case, there was no observed change in smoke opacity. All electronically-controlled engines had their internal diagnostics queried, but no system faults were found. This may be because current diagnostic systems in heavy-duty diesel engines are not designed to recognize faults causing high smoke on the snap-acceleration test. There are also some concerns on the ability of this test to recognize malperformances in electronic systems.

The replacement of the air filter was another common repair performed in one-third of the sample. Turbochargers needed replacement on 4 of 71 turbocharged engines but one was due to leaky oil seals, and was not repaired in this study. In addition, valves were adjusted on several engines, which is part of a general tune-up but has limited impact on smoke opacity.

The frequency of various types of repairs are summarized in Table 5-2, and the similarity in the repair rates to the observed rates in 1990 is noteworthy. As noted, four vehicles were rejected from the program; three due to the extreme wear that would require the engine to be rebuilt in order to restore it to manufacturer's specifications, and one because of extensive tampering that resulted in the dealer's unwillingness to repair the engine. Four additional pre-1991 vehicles were rejected from the program. The SAE J1667 smoke opacity measurements performed by the dealers showed that the engines' opacities were well below the 40 percent criteria established for acceptance. In two of these cases, there were no field tests. Two other vehicles (both buses) powered by DDC 8V-71 engines were field-tested at relatively high opacities (over 50 percent), but tests at the dealership indicated smoke opacity from these engines was below 30 percent.

5.3 SMOKE REDUCTION FROM REPAIRS

On average, all four engine year groups showed significant reductions in smoke from repair. The pre-and post-repair average values are as follows: (excluding the three vehicles where engines were not fully repaired.)

	Average Pre-Repair Opacity	Average Post-Repair Opacity
Pre-1980	65.9	22.4
1980-1987	63.6	20.7
1988-1990	56.0	17.3
1991^+	35.0	21.2

As noted previously, post-repair opacity levels were independent of pre-repair levels, so that larger reductions in opacity were obtained from high emitters. A regression analysis of opacity reduction for pre-1991 vehicles, [defined as (pre-repair opacity) - (post-repair opacity)], indicated the relationship between Δ-opacity to pre-repair opacity was given by:

$$\Delta\text{-opacity} = -24.34 + 1.038 \text{ (Pre-Repair Opacity)} \qquad (r^2 = 0.827)$$
$$= 0.061$$

where r^2 is the standard error of the coefficient.

TABLE 5-1

REPAIR SAMPLE COMPOSITION BY ENGINE MODEL

Manufacturer	Pre-1980		1980-1987		1988-1990		1991+	
	No.	Model	No.	Model	No.	Model	No.	Model
Cummins	7	NTC	13 3	NTC L-10	6 3	NTC L-10	1	L-10
Caterpillar	1 1	1693TA 3306B	7 2	3406 3306	2 1 1	3406 3306 3176	1 1	3176 NTC365
DDC	1 2 1	8V71 6V92 8V92	1 2	8V71 6L71	2	Series 60	3	Series 60
Navistar	1	DT466	1	DT466	--	--	--	--
Mack	1	E6-315	1	EM6-350	3	EC6-350	--	--
Other	--	---	--	--	--	--	2	4BD2C (Isuzu)
TOTALS	**15**	---	**30**	---	**18**	---	**8**	---

TABLE 5-2

DISTRIBUTION OF REPAIR TYPES IN SAMPLE

	Pre-1980		1980-1987		1988-1990		1991+		Rate*
Sample Size	15		29		18		8		70
	A*	R*	A*	R*	A*	R*	A*	R*	%
Air Filter	--	2	--	4	--	--	--	2	12.9
Turbocharger	--	2	--	--	--	1	--	(1)*	4.3
Intake	--	--	--	2	--	1	--	—	2.6 (manifold) 1.4 (Intercooler)
AFRC	5	6	20	7	4	7	1	0	71.4
Injection Pump	2	2	3	10	3	5	1	0	37.1
Overhead	3	2	4	2	9	0	1	0	30.0
Injectors	2	3	2	8	2	8	0	1	37.1
Injection Timing	1	0	1	0	(1)	0	1	0	5.7
Governor	0	0	3	1	0	1	0	0	7.1
Valves	3	0	0	0	2	0	0	0	7.1
Exhaust	0	1	0	0	0	3	0	0	5.7
Electronics	--	--	--	--	2	0	5	0	NA

Numbers in parenthesis are diagnosed but unrepaired defects

* A is Adjusted, R is repaired or replaced. Rate is calculated as a percent of total sample across all model years.

The regression analysis indicated that post-repair opacity was constant, as the coefficient of the relationship between Δ-opacity and pre-repair opacity is close to 1, confirming that post-repair opacity levels were independent of pre-repair levels.

The reductions in opacity obtained for 1991^+ vehicles were similar to those for pre-1991 vehicles, except in two instances where no meaningful reductions were obtained. Because of the small total sample size, no detailed analysis or regression could be performed. The opacity was generally reduced to the 11 to 20 percent opacity range after repair in six vehicles (excluding the two with minimal post-repair smoke reduction.) Hence, the expectation is that a larger sample and better repairs could indicate an average post-repair smoke opacity level of about 15 percent, independent of pre-repair levels. This expectation is also consistent with the fact the certification peak smoke levels for 1991^+ engines have declined 50 to 70 percent from pre-1991 certification levels.

5.4 COSTS OF REPAIRS

The Truck Repair Program had operational cost ceilings of $750 for repair in order to meet budgetary constraints. This amount was more than the standard authorized amount, and was intended as an internal budgetary guideline. It included $500 provided by ARB, and a $250 supplement provided, as necessary, by the respective engine manufacturer. In some cases manufacturers provided additional repair money. In a few instances where the bill was over $1300, the customer agreed to pay the amount not covered by ARB or the engine manufacturer. Other than the three engines for which repairs were incomplete, all other engines were repaired to levels determined to be adequate by the dealers without regard to cost.

Most repairs included a base cost associated with diagnostics and dynamometer testing so that these costs alone, independent of repairs, added a total of $120 to $180 representing 1 to 2 hours of mechanic's time (typically @ $60/hr) and a dynamometer fee of $60 to $70.

The data from the repair invoices submitted to the ARB allowed determination of actual costs of repair. Mechanics did not always provide a breakdown of both part price and labor costs for each component repaired. In order to disaggregate costs of each of the types of repair specified in Table 5-2, data from all 68 repaired vehicles in the sample were utilized to derive data on the cost of repair by component. Each engine had one to six different types of repair among the 12 possible repair categories. Technology differences were recognized for transient air/fuel ratio controls, as costs in this category varied by manufacturer. In other categories of repair, costs were assumed to be relatively independent of manufacturer and model type, and most costs could be determined within a range of $\pm$10 dollars or $\pm$10 percent variability, whichever was larger. Variations within this range reflected different mechanics' costs as well as labor hour differences that may have been caused by engine configuration and vehicle-specific installation details. The determination of individual category-specific repair costs was preceded by an adjustment to the total cost for the cost of diagnostics and a dynamometer test to obtain a total repair cost. Costs were then allocated to various categories of repair and the results are shown in Table 5-3.

Since the dealers were aware of the repair cost expectation of $500, there may have been some incentive to pad the bills with unnecessary labor. It is difficult to confirm if this occurred, but there are six or seven repair bills where the costs are well above expectations based on the repair cost list compiled in Table 5-3, plus diagnostic costs. Some bills may reflect genuine difficulties in diagnostics, or may reflect an engine configuration that is hard to access, so that no attempt was made to second-guess the mechanic. In nine cases, however, the first set of repairs proved unsatisfactory, and these engines underwent a second set of repairs. In four of nine cases, the second set of repairs were performed free, under the repair warranty, by the same dealership or related dealership. Average charges for the second set of repairs for the other four trucks was $652; when averaged over the entire truck sample, the average costs are increased by less than $50. In effect, the dollar amount of incremental costs from incorrect repairs or unnecessary billing is estimated to be at most $50-$100. These excess costs may also occur in real-world situations. Therefore, actual repair costs were used in developing cost effectiveness estimates.

In addition to the above, the costs also include repairs that are only marginally related to the smoke problem. For example, several engines had the valves adjusted, and this can have only very limited impact on smoke. In addition, several engines had all of the injectors replaced even though only one or two may have required replacement. Hence, the stated repair costs for a small group of engines are higher than the minimum required repair costs.

The average costs for the sample of 68 fully-repaired engines are as follows:

Pre-1980 (15 vehicles)	$732
1980-1987 (29 vehicles)	$565
1988-1990 (16 vehicles)	$827
Overall average	$652

Reference to Table 5-2 reveals the reasons why the pre-1980 and 1988-1990 vehicle exhibited higher average costs; in each set, there were some relatively rare repairs that were expensive and inflated the average cost. For the pre-1980 engines, two engines had their turbochargers replaced. In the 1988-1990 vehicle sample, one engine had an intercooler replaced and another had a new injection pump installed. The replacement parts increased costs by over $750 per engine, but the 1980-1987 sample did not have any similar repairs. A more realistic representation is to average the costs across the four model year strata to obtain a mean of $652.

TABLE 5-3
TYPICAL REPAIR COSTS

	Cost Range ($)
Transient Air/fuel Ratio Control	
- Adjust No Air Pressure (Cummins)	120-150
- Replace AFC Plunger/Bellows (Cummins)	300-350
- Adjust AFRC (Caterpillar/Navistar)	200-250
- Replace Throttle Delay (DDC)	275-335
- Replace Puff Limiter (Mack)	100-120
Adjust Governor	100-150
Adjust Fuel Rack	100-130
Adjust Injection Timing	160-220
Fuel Pump - Repair	325-400
Replace	875-950
Replace Unit Injectors (each)*	300-350
Replace Injection Nozzles (6)	300-400
Replace Air Filter	85-135
Replace Turbocharger	700-800
Replace Intercooler	650-750
Reset Valve Timing	90-100
Replace Exhaust Manifold	300-400
Electronic Control Unit Update	120-150
Rebuild Engine*	5000 and Up

* Obtained from direct dealer quotes, as such repairs did not occur in the study.

Reference to Table 5-2 reveals the reasons why the pre-1980 and 1988-1990 vehicle exhibited higher average costs; in each set, there were some relatively rare repairs that were expensive and inflated the average cost. For the pre-1980 engines, two engines had their turbochargers replaced. In the 1988-1990 vehicle sample, one engine had an intercooler replaced and another had a new injection pump installed. The replacement parts increased costs by over $750 per engine, but the 1980-1987 sample did not have any similar repairs. A more realistic representation is to average the costs across the four model year strata to obtain a mean of $652.

Average repair costs for the 8 engines in the 1991^{+} category were only $433. This figure is lower than those for previous years largely because there were no major replacement part costs. This is due to the fact that the trucks are, on average, less than 5 years old, and the cost estimate may be quite reasonable for vehicles 2 to 6 years old (vehicles less than 2 years old are typically covered by manufacturers new engine warranty). However, as these trucks age, it is likely that average repair costs will increase due to the need to replace worn turbochargers, intercoolers, injection pumps and injectors.

Typically, heavy-heavy-duty engines are rebuilt at about 400 to 500 thousand miles of use or every 6 to 8 years. Thus, the finding that all pre-1991 engine groups had similar average repair costs is not surprising, as the engines are constantly renewed. Medium-heavy-duty engines are typically rebuilt at about 250 to 300 thousand miles of use, which corresponds to a similar time interval of 6 to 8 years due to their lower annual use. Hence, repair costs can be modeled as a two-step process, one for the initial six to eight year period and the second during the nine to twenty-five year period.

Costs to rebuild an engine are quite high, starting at $5000 for an "in-frame" rebuild, to nearly double that for a factory rebuild. As noted, eight vehicles were not admitted into the program, and four of these had engines that were candidates for rebuilding. In addition, one of the 71 engines was found to be excessively worn. This engine, along with the four rejected, reflect the fraction of the sample in need of a rebuild. However, the rebuild costs are not counted towards the total program costs since an engine that is very worn has limited remaining operational life. A program such as the HDVIP might force an owner to rebuild the engine at a specific time, but this would constitute accelerating an event that was likely to occur in the relatively short term. As a result, costs of engine rebuild and replacement are not explicitly considered in this analysis.

CHAPTER 6

COSTS OF THE HDVIP AND PSIP

6.1 OVERVIEW

The preceding chapters present a detailed analysis of the technical feasibility of identifying and repairing excessively-smoking heavy-duty diesel vehicles through an amended HDVIP and PSIP. Recommended program cutpoints have been developed and the effectiveness and costs of individual vehicle repairs have been quantified. While the technical integrity of the HDVIP and PSIP has been demonstrated, the overall costs and net benefits associated with putting the programs in place remains to be evaluated. The ratio of overall program costs to program benefits provides a useful measure of program effectiveness, and allows the HDVIP and PSIP to be directly compared to alternative emissions control strategies. This chapter quantifies the overall costs of HDVIP and PSIP implementation and enforcement. The effectiveness of the HDVIP and PSIP (in terms of emissions reductions) will be calculated in Chapter 7, and the cost effectiveness of the programs will be discussed in Chapter 8.

The cost analyses in this report consider the effect of the overall HDVIP and PSIP with the proposed amendments compared to a baseline scenario where there are no heavy-duty vehicle inspection programs. Note that the Staff Report includes analyses of the inspection programs with the amendments proposed by the ARB staff, compared to the original programs as they now exist in the California Code of Regulations.

Overall costs arise from a variety of program requirements, including:

- Labor costs for program administration and enforcement;
- Capital costs for vehicle inspections;
- Costs for vehicle repair;
- Indirect costs due vehicle and driver out-of-service time.

Section 6.2 provides a brief overview of the administrative, implementation, and enforcement features of the previous HDVIP program. The features discussed are to be retained in the proposed HDVIP and PSIP and, therefore, are indicative of how the ARB will implement and administer these proposed programs. Section 6.3 presents estimates of HDVIP and PSIP labor and administrative costs for the affected vehicle fleets. While inspection and administrative costs are dependent on the overall vehicle inspection population, vehicle repair costs are dependent on the number of vehicles that fail HDVIP or PSIP inspections. Therefore, an estimate of HDVIP and PSIP program failure rates is required to develop estimates of total HDVIP- and PSIP-related vehicle repair costs. Section 6.4 presents this required estimate of expected HDVIP and PSIP failure rates and Section 6.5 then presents the resulting estimates of overall program repair costs. Section 6.6 summarizes the component costs developed in Sections 6.1 through 6.5.

6.2 PREVIOUS PROGRAM ADMINISTRATION

Even though enforcement of the HDVIP has been suspended for nearly four years, the administrative features implemented during the program's 1991-1993 enforcement period provide the backbone for both the administrative structure and implementation procedures that will be required when enforcement of the HDVIP is resumed. Moreover, although the PSIP will now be enforced for the first time, the administrative aspects of the HDVIP are readily transferable to the PSIP and thus provide a firm basis for assessing administrative requirements under the proposed PSIP.

From an administrative standpoint, the original HDVIP and PSIP inspection procedures (that were based on the SAE J1243 inspection procedure) are equivalent to those of the SAE J1667 inspection procedure proposed for use upon resumption of the programs. While measured smoke values can differ between the SAE J1667 and J1243 inspection procedures (due to the incorporation of Bessel filtering in the SAE J1667 procedure), the basic steps required to conduct an inspection and enforce the programs do not change. The steps involved in conducting an inspection under the HDVIP are as follows:

- A test site is determined;
- A vehicle is selected for inspection;
- The vehicle is secured for safety;
- The snap-acceleration test is administered;
- A pass/fail determination is made;
- If the vehicle fails, a citation is issued;
- Vehicle owner compliance with the citation is tracked;
- If repairs to clear the citation are not undertaken, additional punitive steps are taken to induce compliance.

Under the PSIP, inspections are performed by the subject fleet and, therefore, ARB administrative steps are limited to:

- An audit of fleet maintenance and inspection records;
- Confirmatory testing of a sample of fleet vehicles (citations are issued for vehicles failing the confirmatory tests and tracked in the same manner as those issued under the HDVIP).

The ARB assembled nine mobile inspection teams, each comprised of two inspectors, to conduct the vehicle testing and citation-issuance aspects of the original HDVIP[1]. These 18 field personnel were supported by two field supervisors and a core of central-office supervisory and

[1] Throughout the remainder of Chapter 6 and all of Chapters 7 and 8, the terminology "original HDVIP" is used when referring specifically to the program administered from 1991 through 1993. Its use is necessary to distinguish the specific features of that program from those of the proposed HDVIP.

personnel were supported by two field supervisors and a core of central-office supervisory and administrative staff. Each of the nine inspection teams conducted vehicle inspections at CHP weigh and truck inspection stations, fleet facilities, and random roadside locations. This same administrative approach is expected to handle vehicle inspection duties under the proposed HDVIP. These same staff will be charged with performing PSIP fleet audits as well.

A typical inspection under the original HDVIP would entail a CHP officer directing a randomly selected vehicle to the ARB test area. ARB staff would then provide the driver with general information on the HDVIP and detailed instructions on performing the test procedure. Operation of the vehicle during the test was the responsibility of the vehicle operator, not ARB staff. To ensure proper engine operation during the test, one of the ARB inspection team members would observe vehicle driver performance during the test (to ensure that the engine was accelerated correctly) while the second team member observed emitted smoke and collected test measurements. Before performing an automated smoke measurement, ARB staff would conduct a visual observation of vehicle smoke during a rapid engine acceleration (with the transmission in neutral). Vehicles emitting significant amounts of smoke during this screening test would be subject to further automated testing; smoke-free vehicles would be released without further action. Based on the smoke opacity values measured during the automated test (on vehicles failing the visual screening test), the vehicle would then either be released without further action or issued a smoke citation if measured smoke levels exceeded applicable standards. This same procedure is applicable to the proposed HDVIP. The smoke-measurement algorithm will be revised to SAE J1667 specifications for the proposed HDVIP and PSIP and does not affect the basic operational steps required to perform an inspection.

Under the original HDVIP, citations for excessive smoke were issued to all vehicles with measured smoke levels above applicable standards. These citations carried a civil penalty designed to promote quick and effective vehicle repairs. Initial citations carried a basic penalty of $800, $500 of which was waived if repairs were completed within 45 days of issuance. Issuance of a second citation within one year carried a basic penalty of $1,800. In instances of further citations (issued within one year of a second citation) an out-of-service order for the vehicle could be issued by the CHP officer. The citation and penalty structure for the proposed HDVIP is identical.

6.3 FLEET ADMINISTRATIVE COSTS

The PSIP imposes both labor and capital costs on fleet facilities subject to the program, and these costs were not associated with the original HDVIP. The following subsections summarize estimates for each of these administrative and capital cost elements.

6.3.1 Fleet Inspection Labor Costs

Implementation of the fleet PSIP will impose labor costs on affected fleets. These costs were not reflected in the original HDVIP program and thus represent new costs to the regulated community. To estimate the impact of PSIP annual inspection requirements on affected fleets, it was assumed that each vehicle inspection would be accomplished by two fleet personnel over a five-minute period. No net vehicle transport labor time or vehicle out-of-service time was assumed for the inspection since it is expected that all PSIP inspections will be accomplished during routine out-of-service periods (e.g., oil changes, periodic maintenance). A fully-burdened hourly labor cost of $50 was assumed for each fleet inspector.

Estimates of the number of fleets and fleet vehicles covered by the PSIP program were developed using the ARB's MVEI7G emissions inventory model and the U.S. Department of the Census' 1992 Census of Transportation: Truck Inventory and Use Survey (TIUS). The ARB's MVEI7G model estimates a total heavy-duty diesel vehicle population of 570,561 vehicles in 1999 and 777,214 vehicles in 2010. ARB has previously estimated that 19 percent of these vehicles are out-of-state registries and, therefore, exempt from PSIP requirements. On this basis, the net California-registered heavy-duty diesel vehicle population is estimated to be 462,164 in 1999 and 629,543 in 2010.

TIUS data indicate that 63.1 percent of heavy-duty vehicles operate in fleets of two or more. TIUS also indicates that there are an average of 31.6 vehicles in each such fleet. Using these data, the total number of fleet vehicles subject to the PSIP in 1999 and 2010 is estimated to be 291,397 and 396,939, respectively. The total number of PSIP-covered fleets is estimated by dividing the number of covered fleet vehicles by the average fleet size, resulting in an estimate of 9,217 covered fleets in 1999 and 12,555 covered fleets in 2010.

Estimating PSIP fleet inspection labor costs is complicated by the fact that not all fleets will elect to perform inspections using "in-house" labor[2] and equipment. Some fraction of fleet owners will opt instead to contract with independent testing services. A number of such services have been established since the implementation of the original HDVIP. Based on these established services, the average cost for contractual testing ranges from $45-$75 per inspection. Since the estimated cost for a smokemeter capable of measuring smoke in accordance with SAE J1667 procedures is estimated to be approximately $5,000 (on average) and have an average useful life of 5 years, a median contractual service testing cost of $60 per vehicle implies that in-house inspection is more economical than contractual inspection only when fleet size exceeds 16 vehicles. The TIUS data indicate that approximately 45.7 percent of heavy-duty vehicle fleets are larger than this size cutoff.

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[2] In-house labor (or in-house staff) refers to staff directly employed and compensated by the fleet owner to perform PSIP vehicle inspections. This terminology is used to distinguish those fleets that purchase smokemeters and assign staff to perform inspection duties from those fleets that hire a contractual inspection service.

On the basis of this analysis, 45.7 percent of fleets (each averaging 31.6 vehicles in size) should find it more economical to purchase smokemeters and perform testing using in-house staff. The remaining fleet vehicles can be more economically tested using contractual inspection services. Disaggregating the total heavy-duty diesel fleet and vehicle population estimates by these fractions yields the following estimates:

4,216 fleets self-testing 133,287 vehicles in 1999, and
5,001 fleets having 158,110 vehicles tested contractually in 1999.

5,743 fleets self-testing 181,563 vehicles in 2010, and
5,001 fleets having 215,376 vehicles tested contractually in 2010.

The net inspection labor costs for fleets opting to use contractual services is zero. Testing contractors do incur costs associated with inspection labor, but these costs accrue as capital expenditures to affected fleets and are thus accounted for in Section 6.3.4 below.

Before a total estimate of fleet inspection labor costs can be developed for those fleets performing inspections using in-house staff, the number of vehicle reinspections due to smoke inspection failure must be added to the number of vehicles initially inspected. As described in Section 6.5.1 below, the estimated failure rates for the HDVIP and PSIP is 13.1 percent in 1999 and 8.6 percent in 2010, resulting in an estimated 17,404 in-house PSIP retests in 1999 and 15,524 in-house retests in 2010. Combining these retest estimates with estimates for the number of initial inspections, the per-vehicle inspection time, the number of fleet personnel required to perform an inspection, and the hourly cost of labor as presented above, the total fleet labor cost due to HDVIP and PSIP implementation is estimated to be \$1.26 million in 1999 and \$1.64 million in 2010, calculated as follows:

labor cost in 1999 = 2 staff x \$50/hr x 150,691 inspections x 5/60 hrs/inspection

= \$1.26 million

labor cost in 2010 = 2 staff x \$50/hr x 197,086 inspections x 5/60 hrs/inspection

= \$1.64 million

6.3.2 Fleet Capital Costs

Under the PSIP, covered fleets will either be required to purchase and operate smokemeters capable of measuring smoke in accordance with the SAE J1667 procedure or, alternatively, contracting with private testing services to have the required PSIP inspections performed. While it is possible that a fraction of covered fleets own or would purchase such equipment independent of PSIP requirements, it is not possible to estimate the magnitude of this fraction. Therefore, it is assumed that each of the fleets covered by the PSIP will be required to either purchase a SAE

J1667-compliant smokemeter or contract for inspection services. As discussed in Section 6.3.1 detailing fleet labor costs, 9,217 fleets are estimated to be subject to the PSIP in 1999. The number of covered fleets is estimated to increase to 12,555 in 2010. Of these, 4,216 fleets were estimated to perform in-house testing in 1999 and 5,743 fleets were estimated to perform in-house testing in 2010. Each of these fleets will require at least one SAE J1667-compliant smokemeter. It is likely that some of the larger fleets will require multiple smokemeters to accommodate their entire covered vehicle population. According to the TIUS data used to estimate PSIP fleet populations, approximately 18.7 percent of covered fleets have more than 100 vehicles. Using this fraction as an estimate of the fraction of fleets that will need to purchase two smokemeters to satisfy PSIP testing requirements, an overall average of 1.187 smokemeters per in-house testing fleet will be required under the PSIP (0.187 times 2 plus 0.813 times 1).

As indicated in Section 6.3.1, SAE J1667-compliant smokemeters are estimated to cost approximately $5,000 per unit (on average). Since 4,216 fleets are expected to purchase an average of 1.187 smokemeters each in 1999, the total capital outlay in 1999 is estimated to be $25.02 million. By 2010, an additional 1,527 fleets (5,743 fleets in 2010 minus 4,216 fleets in 1999) will need to purchase an average of 1.187 smokemeters for an additional capital outlay of $9.06 million. A straight line depreciation of these costs over the estimated five-year equipment life results in estimated annual PSIP capital costs due to smokemeter purchase of $5.00 million in 1999 and $6.82 million in 2010.

Fleets that contract with private testing services to perform PSIP inspections will incur annual capital costs for these services. As detailed in Section 6.3.1, it is estimated that 158,100 vehicles will be subject to contractual testing in 1999 and 215,376 vehicles will be subject to contractual testing in 2010. On the basis of the PSIP failure rates of 13.1 percent in 1999 and 8.6 percent in 2010 (as estimated in Section 6.5.1), an additional contractual inspection load of 20,646 retests in 1999 and 18,415 retests in 2010 is expected. Combining these retest estimates with the estimates for the number of initial inspections and the per-inspection cost estimate of $60 (as described in Section 6.3.1), the total fleet capital cost outlay for contractual PSIP inspections is estimated to be $10.73 million in 1999 and $14.03 million in 2010.

6.4 FAILURE RATES FROM THE RANDOM TRUCK OPACITY SURVEY

In addition to the HDVIP and PSIP administrative costs estimated in Section 6.3, vehicle owners will also incur costs due to vehicle repair, lost time, and improved maintenance practices. Each of these costs depends either on the number of vehicles that fail HDVIP or PSIP inspections or the risk of inspection failure, both of which are defined by the HDVIP and PSIP failure rate. Therefore, an estimate of the inspection program failure rates in 1999 and 2010 is required before the additional vehicle owner costs can be defined. This section details the methodology by which the required failure rate estimates were developed and presents the resulting estimates.

6.4.1 The Random Truck Opacity Survey

Section 3.3 describes the Random Truck Opacity Survey[3] conducted by the ARB between August and November of 1996. Because the Random Truck Opacity Survey data is critical to the estimation of heavy-duty diesel vehicle failure rates under the proposed HDVIP and PSIP (and thus critical to the estimation of vehicle repair costs, etc.), background material on the survey is reproduced here so that a full understanding of the failure rate analysis is possible.

The Random Truck Opacity Survey included the application of the SAE J1667 snap-acceleration smoke test procedure to randomly-selected heavy-duty diesel vehicles in an effort to develop a profile of heavy-duty diesel vehicle smoke characteristics in California. Through this study, SAE J1667 smoke test results were obtained for a usable sample of 1002 vehicles (as described in Section 6.4.2 below, testing results for 190 vehicles were unusable due to incomplete or erroneous data). Tables 6-1 and 6-2 present the breakdown of test engines by manufacturer, model year group, and size category. Table 6-3 is a reproduction of Table 3-1, that presents a breakdown of Random Truck Opacity Survey testing locations.

All smoke testing performed under the Random Truck Opacity Survey was conducted in strict accordance with SAE J1667 procedures (see Appendix A). As specified under the SAE J1667 test procedure, data other than actual smoke test results are needed in order to make a standardized determination of emitted smoke since both smoke production rates and smoke measurements can be dependent on test conditions. Smoke production rates, which are sensitive to combustion air/fuel ratios, can vary with meteorological conditions that affect air density. Even under identical meteorological conditions, smoke measurement, which relies on a determination of the degree of light absorption and scattering, is sensitive to the distance the transmitted light must pass between its source and a detector (this transmission distance is known as the optical path length). Because of this dependency, two engines with identical smoke generation rates but different diameter exhaust stacks will generate different opacity readings (using full-flow end-of-line smokemeters). The SAE J1667 test procedure includes corrections to address both phenomena and produce standardized smoke measurements.

Data required to perform the necessary SAE J1667 smoke measurement corrections include the effective optical path length to correct for different exhaust stack sizes and meteorological parameters to correct for differences in ambient air density. For full-flow end-of-line type smokemeters, the effective optical path length is generally equivalent to exhaust stack diameter. For partial-flow sampling smokemeters, the effective optical path length for smoke measurement is a function of the meter's internal sampling chamber. However, partial-flow sampling smokemeters require the user to input the stack diameter for the test vehicle and actual smoke measurements are internally corrected to this input "path length" prior to reporting. As a result, both end-of-line and partial-flow smokemeters report smoke measurements based on the stack

[3] Although formally known as the Random Truck Sampling Survey, the test program measured smoke emissions from all types of in-use heavy-duty diesel vehicles operating on California roadways, including buses.

diameter of the test vehicle. To correct for differences in ambient air density, parameters such as dry and wet bulb temperatures and barometric pressure must be measured at the time of testing. The Random Truck Opacity Survey included a collection of all such required data as well as additional data to classify the subject test vehicle and engine population according to gross vehicle weight rating (GVWR) class and model year.

6.4.2 Corrections to the Random Truck Opacity Survey Database

Before the raw data collected under the Random Truck Opacity Survey could be analyzed to estimate HDVIP and PSIP failure rates, optical path length and ambient conditions adjustments were undertaken to construct a database consistent with SAE J1667 test procedure requirements. To undertake these corrections, a minimum set of data was required which included: measured opacity, vehicle stack diameter, engine horsepower, ambient temperature, and barometric pressure. Additionally, parameters such as engine model year and GVWR class were needed to properly discriminate trends in the required failure rate analysis.

TABLE 6-1

DISTRIBUTION OF HHDDV[1] IN THE RANDOM TRUCK OPACITY SURVEY BY MANUFACTURER

Engine Make	Model Year Group					Total Tested	Percent Tested
	Pre-1980	1980-83	1984-87	1988-90	1991+		
Caterpillar	6	4	30	34	81	155	26.2
Cummins	47	46	109	63	73	338	57.1
DDC	3	1	6	10	64	84	14.2
Hino	0	0	0	1	1	2	0.3
Mack	1	0	0	1	5	7	1.2
Navistar	0	0	1	0	1	2	0.3
Unknown	0	0	0	0	4	4	0.7
All Makes	57	51	146	109	229	592	100.0

[1] Heavy-heavy-duty diesel vehicles.

TABLE 6-2

DISTRIBUTION OF MHDDV[1] IN THE
RANDOM TRUCK OPACITY SURVEY BY MANUFACTURER

Engine Make	Model Year Group					Total Tested	Percent Tested
	Pre-1980	1980-83	1984-87	1988-90	1991+		
Caterpillar	3	7	12	15	27	64	15.6
Cummins	24	40	76	39	62	241	58.8
DDC	1	1	10	4	18	34	8.3
Ford	0	0	3	2	0	5	1.2
Hino	0	0	3	4	3	10	2.4
Iveco	0	0	0	2	0	2	0.5
Mack	0	0	4	5	3	12	2.9
Navistar	0	0	1	2	3	6	1.5
Nissan	0	0	0	0	1	1	0.2
Volvo	0	0	0	0	2	2	0.5
White	0	0	1	0	0	1	0.2
Unknown	1	2	6	8	15	32	7.8
All Makes	29	50	116	81	134	410	99.9

[1] Medium-heavy-duty diesel vehicles.

TABLE 6-3

DISTRIBUTION OF RANDOM TRUCK OPACITY SURVEY TEST LOCATIONS

Test Location	Model Year Group					Total Tested	Percent Tested
	Pre-1980	1980-83	1984-87	1988-90	1991+		
Northern California Locations							
Antelope	15	8	29	16	30	98	9.8
Cordelia	10	6	19	15	24	74	7.4
Los Banos	0	3	9	2	7	21	2.1
Northern Total	25	17	57	33	61	193	19.3
Southern California Locations							
Cache Creek	0	0	0	0	5	5	0.5
Castaic	5	7	22	26	46	106	10.6
Desert Hills	5	7	12	9	18	51	5.1
Grapevine	0	5	15	7	14	41	4.1
Rainbow	16	17	44	34	70	181	18.1
San Onofre	29	35	96	61	120	341	34.0
Temecula	2	6	5	9	8	30	3.0
Winterhaven	4	7	11	11	21	54	5.4
Southern Total	61	84	205	157	302	809	80.7
All Locations							
Sample Total	86	101	262	190	363	1,002	100.0

The Random Truck Opacity Survey was designed to collect data for all required SAE correction and failure rate analysis parameters. Nevertheless, there were cases when a complete set of data was not collected for each vehicle surveyed. Reasons for incomplete data collection vary, but include such influences as data entry error, missing engine and vehicle tags (from which GVWR and model year are determined), measurement equipment malfunction, etc. In total, 1192 vehicles were sampled under the Random Truck Opacity Survey. Test records for 190 of these vehicles were eliminated through quality assurance checks that revealed missing or erroneous smoke measurement, vehicle or engine identification, effective optical path length, or meteorological data. Some of these records could have been retained despite the lack of valid meteorological data since the Random Truck Opacity Survey was limited to low-altitude test sites where the degree of meteorological influence is generally expected to be minor. Nevertheless, these records were eliminated from further analysis to ensure strict adherence to SAE J1667 test procedures. As a result, a total of 1002 usable test records were collected.

Of the 1002 available records from the Random Truck Opacity Survey, only about 54 percent included specific engine model year data. The remaining 46 percent of test records did not indicate the applicable test engine model year due to missing engine labels, data acquisition errors, or data entry errors. These 46 percent did, however, include data on the model year of the subject test vehicle. To maximize available analysis data, a comparison of the 54 percent of test records (538 records) with both vehicle and engine model year data was made. Ninety (90) percent of these records (484 records) indicated a difference of no more than one year between the two indicated model years. Forty-seven (47) percent indicated identical vehicle and engine model years, 42 percent indicated an engine one model year older than the vehicle, and 1 percent indicated a vehicle one year older than the engine. Based on this observed similarity of engine and vehicle model years, test record vehicle model year was used as a surrogate for test engine model year when the latter was not available.

The measured smoke readings on all usable Random Truck Opacity Survey test records were corrected to their SAE J1667 standard optical path length and standard ambient test condition equivalents. SAE J1667 optical path length standards vary between 2 and 5 inches depending on engine horsepower. About two-thirds of the smoke test records included a specified engine horsepower. For the other one-third of test engines, a 5-inch standard optical path length (applicable to engines of 301 horsepower and above) was selected if the test engine was identified as being in the heavy-heavy-duty class and a 4-inch standard optical path length (applicable to engines of 201 to 300 horsepower) was selected if the test engine was identified as being in the medium-heavy-duty class.

Smokemeters from three different manufacturers were used in the Random Truck Opacity Survey. Two were full-flow end-of-line smokemeters such that the effective optical path length during testing was equal to the measured diameter of the vehicle exhaust stack. The third smokemeter was a partial-flow sampling-type meter with an internal effective optical path length of 100 millimeters. However, the partial-flow meter performed an internal stack diameter smokemeter was a partial-flow sampling-type meter with an internal effective optical path length of 100 millimeters. However, the partial-flow meter performed an internal stack diameter correction so that the effective path length of reported smoke measurements was equal to the test vehicle stack diameter. Therefore, the measured exhaust stack diameter was used as the optical path length of the uncorrected smoke measurements for all Random Truck Opacity Survey test records.

Figure 6-1 presents the distribution of the magnitude of SAE J1667 optical path length corrections applied to Random Truck Opacity Survey data. Negative corrections indicate that the corrected opacity is less than the measured opacity. As indicated, about 75 percent of all Random Truck Opacity Survey measurements were corrected by 1 opacity-percent or less, with 89 percent of measurements corrected by 5 opacity-percent or less. The remainder of corrections mostly decrease measured opacity by 5 to 10 percentage points. Corrections in this range are generally indicative of large-diameter exhaust stack measurements being corrected to smaller SAE J1667 standard stack diameters (most notably 5-inch measured path lengths being corrected to 4-inch standard path lengths at moderate to high opacity levels).

Following the application of the standardized optical path length correction, an additional correction designed to account for ambient condition differences (i.e., air density) was applied to each test record as prescribed by the SAE J1667 test procedure. Under SAE J1667, all measured opacities are corrected to a reference dry air density of 0.0722 pounds-mass per cubic foot. While this ambient correction can be substantial for large variations in air density, the elevation and temperature ranges of the Random Truck Opacity Survey were fairly restricted as indicated by the distribution of applied corrections shown in Figure 6-1. Sixty-seven (67) percent of ambient corrections were 1 opacity-point or less, 87 percent were 2 opacity-points or less, and 98 percent were 5 opacity-points or less. As was the case with the path length correction described above, negative corrections indicate an adjustment to reduce measured opacity.

6.4.3 <u>Expected HDVIP and PSIP Failure Rates</u>

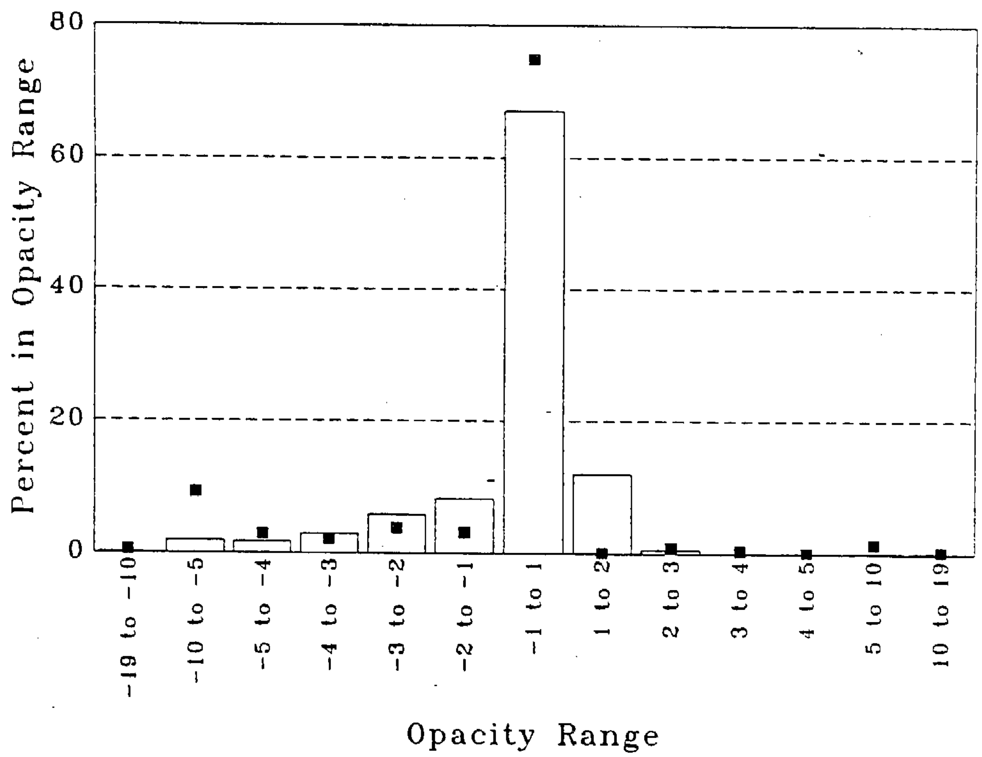
The corrected Random Truck Opacity Survey data was analyzed to determine the failure rates that can be expected upon enforcement of the cutpoints documented in Chapter 4. Since the failure rate for a specific vehicle class can be expected to increase (especially in the absence of an active smoke enforcement program) as engines age and deteriorate, the form of the failure rate deterioration function must be estimated to accurately forecast expected failure rates for different smoke enforcement years of program evaluation. To estimate this deterioration function, the Random Truck Opacity Survey data was analyzed by vehicle class and engine model year to determine if statistical trends in failure rate with engine age were observable.

In the initial analysis of the Random Truck Opacity Survey database, it was apparent that the sample size of certain model year engines was not large enough to isolate opacity trends. As indicated in Table 6-4, sample sizes for model years 1984 through 1996 are fairly consistent and adequately large to accommodate individual analysis. Samples for the remaining model years are not of sufficient size to allow age-based trends in smoke emissions to be distinguished from other potential sources of variability. Nevertheless, data for these older engines is important, and an alternative analytical approach based on the aggregation of older model years was employed.

Heavy-duty diesel engines from 1980 and earlier utilize similar, relatively unsophisticated, mechanically-controlled technology and have accumulated mileage to the degree that virtually all have undergone multiple engine rebuilds and can be expected to have similar smoke emissions.

FIGURE 6-1

DISTRIBUTION OF OPACITY CORRECTIONS



Path Length Correction distribution is plotted as points.
Ambient Air Density Correction distribution is plotted as bars.

Engines in the 1981 through 1983 model year strata represent the last group of heavy-duty diesel engines certified for sale under a steady-state emissions-testing procedure. All were certified to the same set of standards and will have accumulated similar mileages and, therefore, should possess similar characteristics of smoke emissions. Based on these similarities, all 1980 and earlier model year test records were aggregated into one group and all 1981 through 1983 model year test records were aggregated into a second group for statistical analysis purposes. Because of their small sample size, all 1997 vehicles in the Random Truck Opacity Survey database were aggregated with 1996 vehicles for analysis. This aggregation process resulted in fairly consistent sample sizes across all analysis model year groups as shown in Table 6-4.

Before proceeding with failure rate model construction using the Random Truck Opacity Survey database, an evaluation was undertaken to determine whether a single failure rate model could be developed for all test vehicles or whether a distinct model would be required for various subsets of the heavy-duty diesel vehicle fleet. Figures 6-2 through 6-11 present observed opacity distributions (after the application of the smoke measurement standardization procedures discussed in Section 6.4.2 above) for various model year groupings of the medium-heavy- and heavy-heavy-duty diesel vehicles tested. The selected model year groupings are designed to reflect periods of fairly similar engine technology. Engine model yearsof 1980 and earlier are presented as a single group and represent relatively unsophisticated, mechanically-controlled engines. The 1980 through 1983 engine group reflects those engines certified just prior to the advent of transient emissions certification requirements, and the 1984 through 1987 engine group reflects the first generation of engines certified to meet those requirements. The 1988 through 1990 model year grouping recognizes the advent of PM emissions testing requirements and, finally, the 1991 and newer engine grouping reflects the beginning and evolution of the era of stringent NO_x and PM emissions control.

As illustrated in Figures 6-2 through 6-11, there is a substantial difference between the opacity distributions for older medium-heavy- and heavy-heavy-duty diesel vehicles. The opacity distributions for older medium-heavy-duty diesel vehicles reflect a much greater fraction of vehicles in the low opacity ranges than is the case for heavy-heavy-duty diesel vehicles. However, this difference steadily declines with newer model years and no difference is evidenced at all for the group of 1991 and newer vehicles. It is postulated that this relationship primarily results from the generally lower level of penetration of turbocharger technology in the medium-heavy engine class. Analysis performed in support of the TSD (1990 TSD) for the original HDVIP revealed that naturally-aspirated engines are much less likely to fail the snap-acceleration test, and this is reflected in the lower failure rate for medium-heavy-duty diesel vehicles. Table 6-5 presents basic descriptive statistics for the same vehicle groupings that further illustrate this trend. Based on these observations and the fact that the recommended HDVIP cutpoints vary for pre-1991 vehicles and 1991 and newer vehicles, separate failure rate model forms were investigated for the recommended HDVIP opacity cutpoints. Various linear, second order, and logarithmic constructions were evaluated through least-squares regression analysis, and the functions presented in Figures 6-12 through 6-14 were selected as the most appropriate descriptive models for the SAE J1667 database.

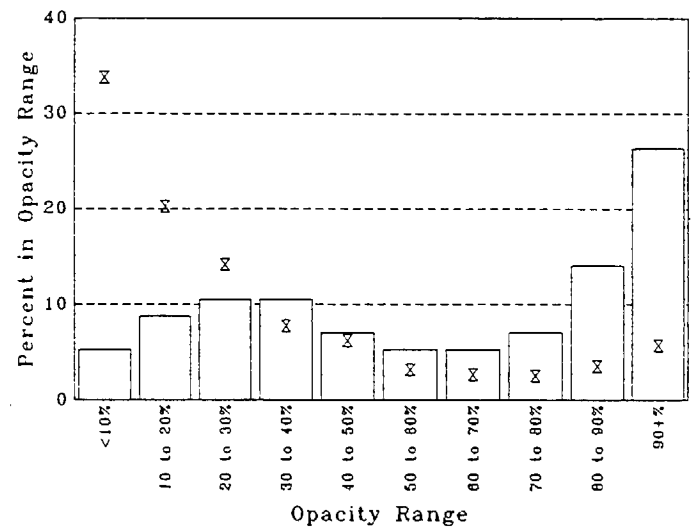
TABLE 6-4

SAMPLE SIZES FROM THE RANDOM TRUCK OPACITY SURVEY

Sample Sizes Before Aggregation					
Model Year	**HHDDV**	**MHDDV**	**Model Year**	**HHDDV**	**MHDDV**
1968	1	0	1983	18	17
1969	1	1	1984	36	34
1970	3	2	1985	38	30
1971	1	2	1986	33	25
1972	3	0	1987	39	27
1973	2	2	1988	38	26
1974	4	2	1989	45	28
1975	2	3	1990	26	27
1976	3	0	1991	27	17
1977	13	5	1992	40	20
1978	11	6	1993	36	23
1979	13	6	1994	38	24
1980	15	13	1995	59	30
1981	11	8	1996	26	19
1982	7	12	1997	3	1
Sample Sizes after Aggregation					
Model Year	**HHDDV**	**MHDDV**	**Model Year**	**HHDDV**	**MHDDV**
Pre-1980	57	29	1990	26	27
1980-1983	51	50	1991	27	17
1984	36	34	1992	40	20
1985	38	30	1993	36	23
1986	33	25	1994	38	24
1987	39	27	1995	59	30
1988	38	26	1996-1997	29	20
1989	45	28			

FIGURE 6-2

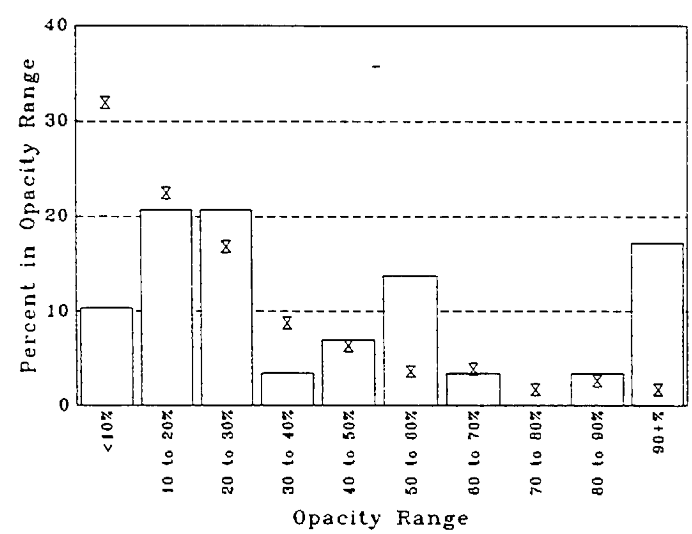
OPACITY DISTRIBUTION FOR PRE-1980 HHDDV



Hourglass markers indicate the distribution of opacities for the entire sample (all model years). There are 57 pre-1980 observations in the entire 592 observation HHDDV sample.

FIGURE 6-3

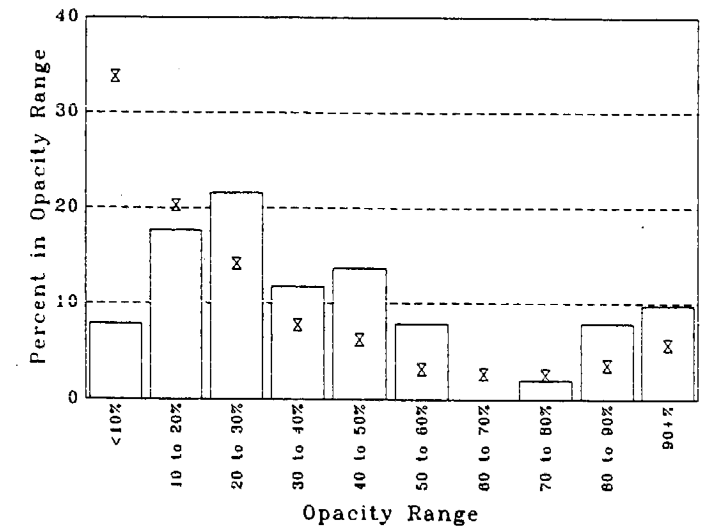
OPACITY DISTRIBUTION FOR PRE-1980 MHDDV



Hourglass markers indicate the distribution of opacities for the entire sample (all model years). There are 29 pre-1980 observations in the entire 410 observation MHDDV sample.

FIGURE 6-4

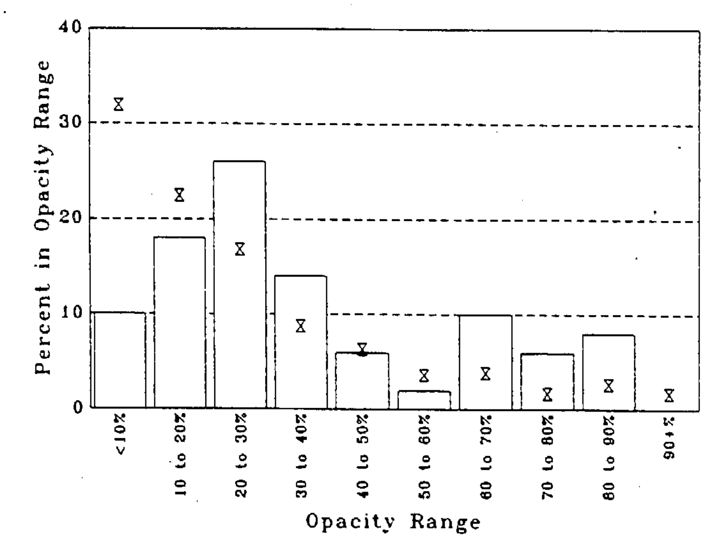
OPACITY DISTRIBUTION FOR 1980-83 HHDDV



Hourglass markers indicate the distribution of opacities for the entire sample (all model years). There are 51 1980-83 observations in the entire 592 observation HHDDV sample.

FIGURE 6-5

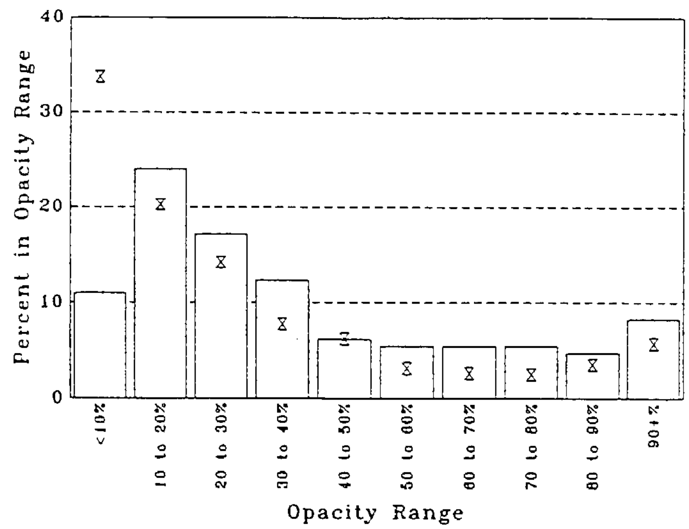
OPACITY DISTRIBUTION FOR 1980-83 MHDDV



Hourglass markers indicate the distribution of opacities for the entire sample (all model years). There are 50 1980-83 observations in the entire 410 observation MHDDV sample.

FIGURE 6-6

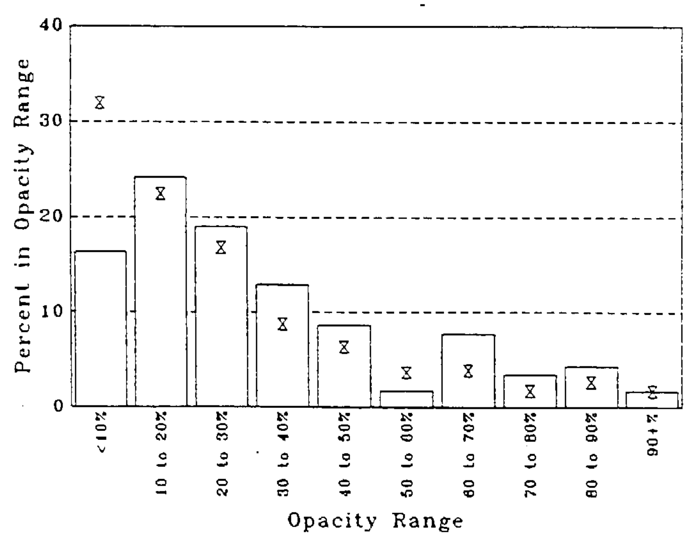
OPACITY DISTRIBUTION FOR 1984-87 HHDDV



Hourglass markers indicate the distribution of opacities for the entire sample (all model years). There are 146 1984-87 observations in the entire 592 observation HHDDV sample.

FIGURE 6-7

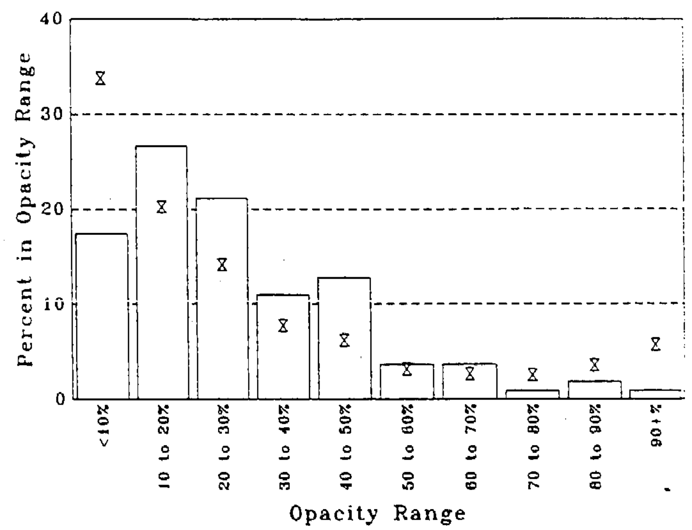
OPACITY DISTRIBUTION FOR 1984-87 MHDDV



Hourglass markers indicate the distribution of opacities for the entire sample (all model years). There are 116 1984-87 observations in the entire 410 observation MHDDV sample.

FIGURE 6-8

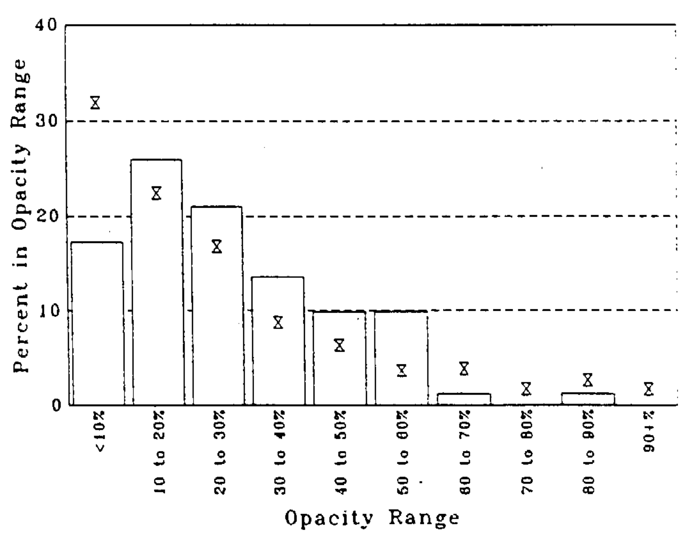
OPACITY DISTRIBUTION FOR 1988-90 HHDDV



Hourglass markers indicate the distribution of opacities for the entire sample (all model years). There are 109 1988-90 observations in the entire 592 observation HHDDV sample.

FIGURE 6-9

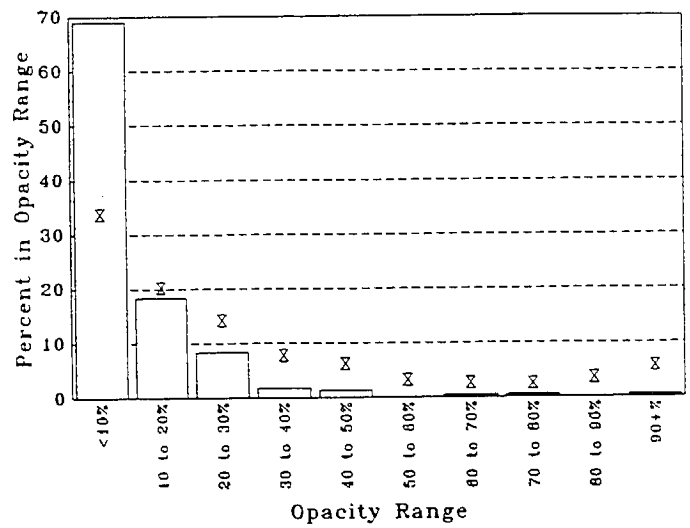
OPACITY DISTRIBUTION FOR 1988-90 MHDDV



Hourglass markers indicate the distribution of opacities for the entire sample (all model years). There are 81 1988-90 observations in the entire 410 observation MHDDV sample.

FIGURE 6-10

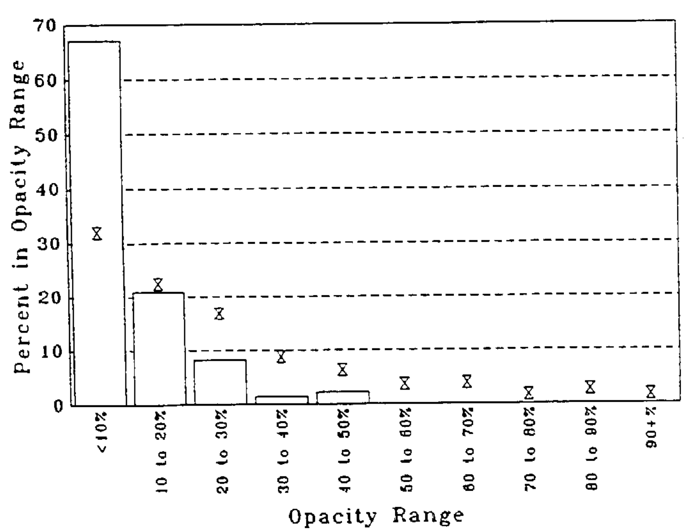
OPACITY DISTRIBUTION FOR 1991⁺ HHDDV



Hourglass markers indicate the distribution of opacities for the entire sample (all model years). There are 229 1991 and newer observations in the entire 592 observation HHDDV sample.

FIGURE 6-11

OPACITY DISTRIBUTION FOR 1991⁺ MHDDV



Hourglass markers indicate the distribution of opacities for the entire sample (all model years). There are 134 1991 and newer observations in the entire 410 observation MHDDV sample.

TABLE 6-5

BASIC OPACITY STATISTICS FOR THE RANDOM TRUCK OPACITY SURVEY DATABASE

Model Year	Heavy-Heavy-Duty Diesel Vehicles				Medium-Heavy-Duty Diesel Vehicles			
	Vehicles Tested	Median Opacity	Mean Opacity	Standard Deviation	Vehicles Tested	Median Opacity	Mean Opacity	Standard Deviation
Pre-1980	57	65.4	59.6	31.8	29	28.3	42.7	31.6
1980-83	51	31.8	40.7	27.1	50	27.5	35.6	24.1
1984-87	146	27.9	38.2	27.8	116	25.6	31.4	23.7
1988-90	109	22.3	27.1	19.4	81	22.8	25.9	17.4
1991 and Newer	229	6.4	9.8	11.8	134	6.5	9.4	8.7

For pre-1991 heavy-heavy-duty diesel vehicles, the best-fit regression model was determined as:

$$\text{Failure Rate} = -0.727934 + 0.396924\,(\ln \text{Age}) \qquad r^2 = 0.84$$

$$\begin{array}{cc} (0.1579) & (0.0648) \\ (t=-4.6) & (t=6.1) \end{array}$$

where age is determined as 1997 minus the test engine model year.

For pre-1991 medium-heavy-duty diesel vehicles, the best fit regression model was determined as:

$$\text{Failure Rate} = -0.509942 + 0.276716\,(\ln \text{Age}) \qquad r^2 = 0.87$$

$$\begin{array}{cc} (0.1006) & (0.0413) \\ (t=-5.1) & (t=6.7) \end{array}$$

The reduced-age coefficient for medium-heavy-duty diesel vehicles reflects the lower failure rate deterioration for those vehicles (relative to heavy-heavy-duty diesel vehicles) and the magnitude of this reduction is easily observed by comparing Figures 6-12 and 6-13. During the 1997 calendar year, the medium-heavy-duty model predicts a failure rate of about 3 percent for 1990 engines rising to about 25 percent for 1976 engines. Its heavy-heavy-duty counterpart predicts a rise from about 4 percent for 1990 engines to 48 percent for 1976 engines.

The similarity in failure rate behavior for 1991 and newer medium-heavy-duty and heavy-heavy-duty diesel vehicles was confirmed when separate models were evaluated for each. As expected, the resulting model coefficients were virtually identical and as a result, a combined medium-heavy-duty and heavy-heavy-duty engine model was constructed. Since the observed data (see Figure 6-14) indicated a zero failure rate for engines up to two years of age, a lagged model construction based on engine "age minus two" was employed. The resulting model developed for all 1991 and newer heavy-duty engines was:

$$\text{Age} \leq 2: \quad \text{Failure Rate} = 0$$

$$\text{Age} > 2: \quad \text{Failure Rate} = 0.020152\,(\text{Age} - 2) \qquad r^2 = 0.84$$

$$\begin{array}{c} (0.0045) \\ (t=4.5) \end{array}$$

For all three failure rate models, age was measured relative to 1997 (i.e., a 1991 engine was assumed to be six years old, a 1977 engine 20 years old). It should also be noted that the best fit model for 1991 and newer engines was actually a second order lagged age model, where a correlation coefficient of 0.94 was observed. (Visual examination of Figure 6-14 easily illustrates the superiority of the second order fit.) However, such a model would imply inordinate failure rate increases as engines age beyond 10 years or so. It is believed that as 1991 and newer engines age beyond the six years currently in evidence, the selected linear model will more accurately describe engine performance than the alternative second order model that was rejected.

FIGURE 6-12

FAILURE RATE RELATION FOR PRE-1991 HHDDV

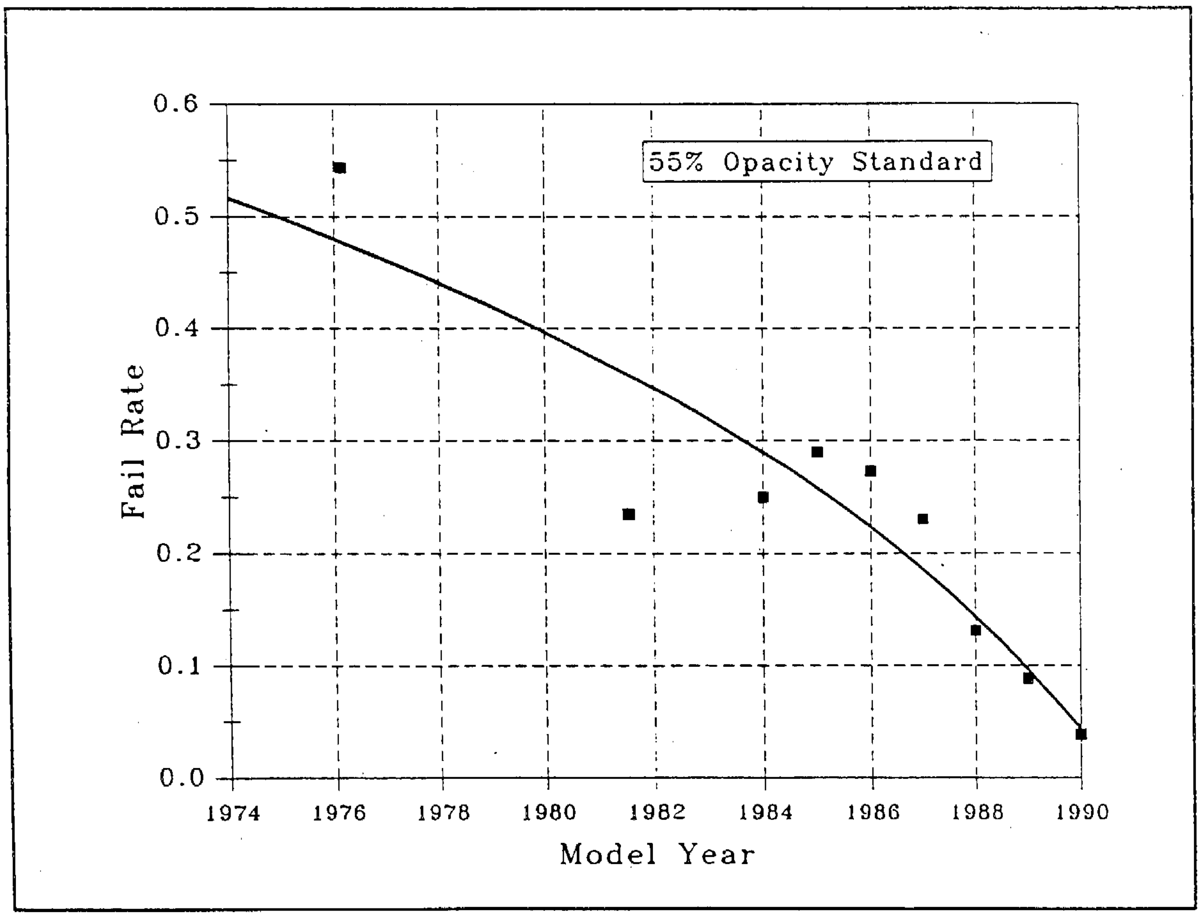


FIGURE 6-13

FAILURE RATE RELATION FOR PRE-1991 MHDDV

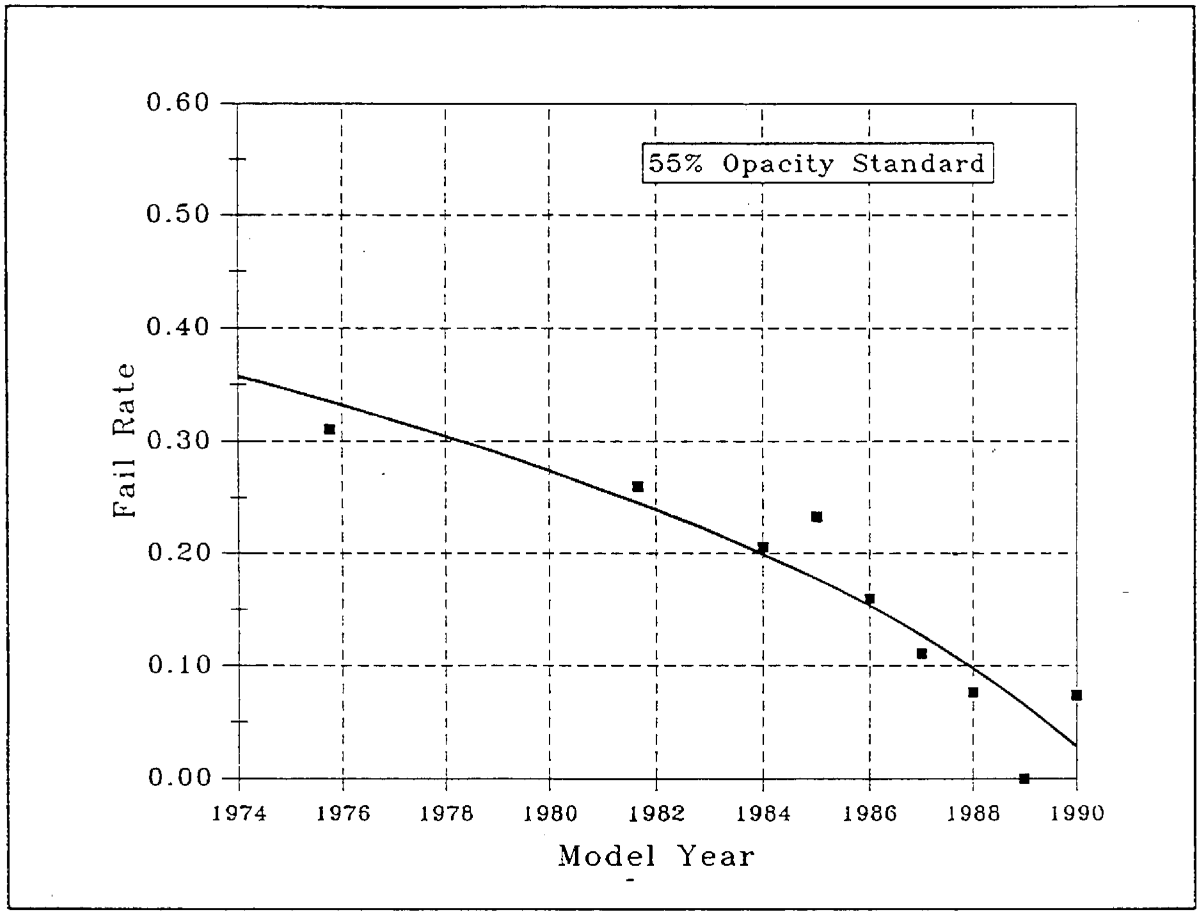
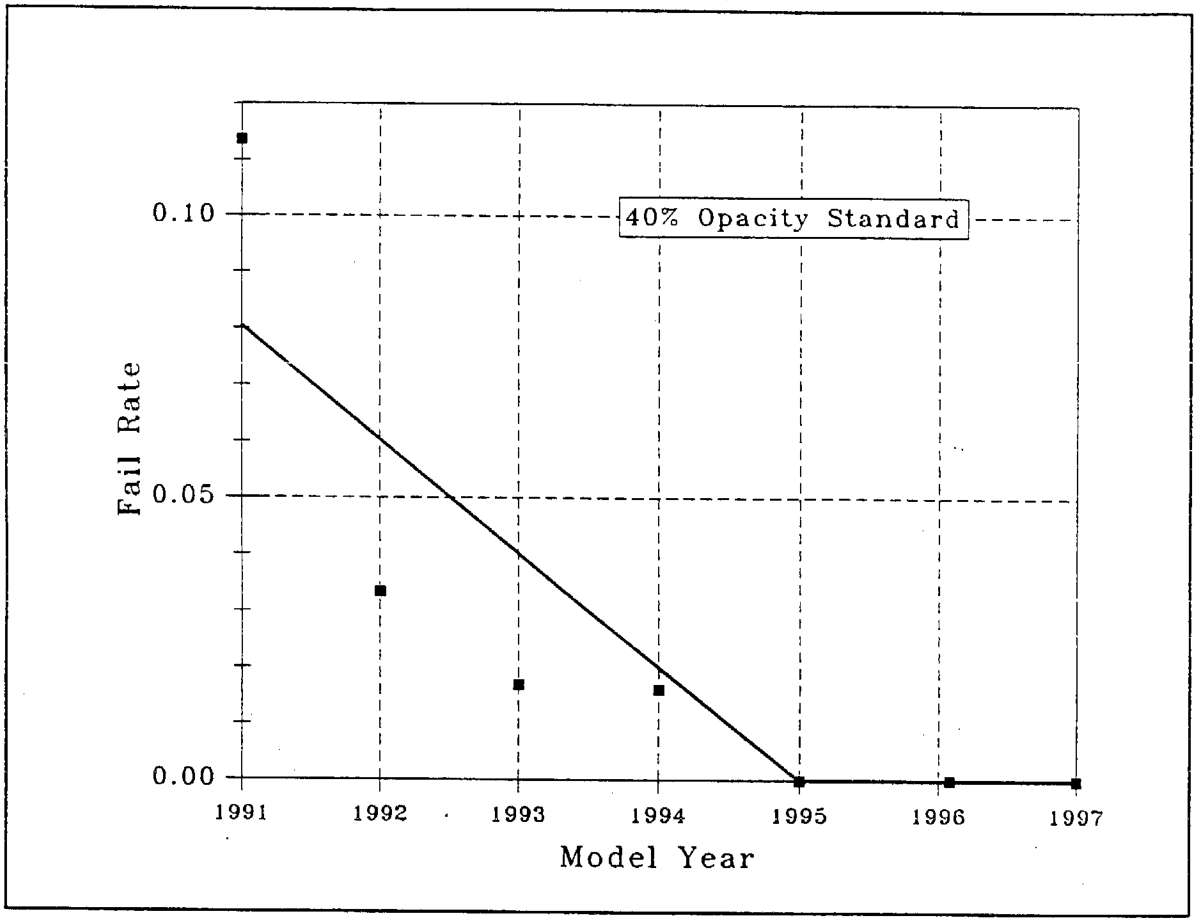


FIGURE 6-14

FAILURE RATE RELATION FOR POST-1990 HHDDV AND MHDDV



Using the models presented above, expected failure rates were developed for the 1999 and 2010 HDVIP and PSIP evaluation years. Since criteria pollutant benefits associated with HDVIP and PSIP implementation are determined using the ARB motor vehicle emissions inventory model MVEI7G, failure rates were determined for vehicles up to 35 model years in age. Table 6-6 and Figures 6-15 and 6-16 present the estimated failure rates. The discontinuities observed around the 1990 and 1991 model year vehicle failure rates reflect the interface of the respective proposed 55 and 40 percent opacity cutpoints. Applying these model year-specific failure rates to the heavy-duty diesel vehicle distribution forecast by the ARB's MVEI7G emission factor model yields estimated fleet average failure rates of 13.1 percent in 1999 and 9.2 percent in 2010.

Note that the tabulated failure rates do not account for the improvement in vehicle maintenance that is expected to accrue following HDVIP and PSIP implementation. This is consistent with the use of MVEI7G to determine the programs' emission reduction benefits. Since MVEI7G estimates all smoke enforcement program impacts on the basis of an adjustment to a baseline (i.e., no HDVIP and PSIP) emission rate regardless of the evaluation year, it is critical that MVEI7G inputs reflect the aggregate impacts of the HDVIP and PSIP in any given year. Therefore, while the actual HDVIP and PSIP failure rate in 2010 will be less than that indicated in Table 6-6, due to improved vehicle maintenance, (lower by about 7 percent as described in Sections 6.5.1 and 6.5.2 below), the overall impact of the HDVIP and PSIP (in terms of improved maintenance plus failure-driven repairs) will be equivalent to the baseline failure rates presented in Table 6-6.

6.5 PROGRAM COSTS TO VEHICLE OWNERS

Both the HDVIP and PSIP will impose costs on the regulated community. Vehicle owners will be required to repair failed vehicles and clear the associated smoke citations issued by the ARB. Implementation of the HDVIP and PSIP will also induce a fraction of vehicle owners to expend funds on additional vehicle maintenance to avoid potential citation costs. Based on the failure rate expectations presented in Section 6.4 and experience gained from administration of the original HDVIP, estimates can be derived for these vehicle owner costs.

6.5.1 Costs of Failed Vehicle Repair

The total costs of vehicle repair depend on two factors: (1) the number of malmaintained vehicles identified by the HDVIP and PSIP and subsequently repaired, and (2) the fraction of vehicles voluntarily repaired in response to HDVIP and PSIP implementation (i.e., the deterrence effect of the programs). The number of malmaintained vehicles identified by the HDVIP and PSIP is dependent on the fraction of vehicles inspected, the fraction of inspected vehicles failed, the fraction of those failures that are repaired, and the average vehicle repair cost.

The fraction of vehicles inspected is a function of the number of inspections that are performed under the HDVIP and the PSIP, minus the fraction of vehicles inspected under both programs. The ARB estimates that approximately 40,000 HDVIP inspections will be performed annually.

TABLE 6-6
FAILURE RATES FOR PROGRAM EVALUATION YEARS

1999 Evaluation Year			2010 Evaluation Year		
Model Year	HHDDV Failure Rate	MHDDV Failure Rate	Model Year	HHDDV Failure Rate	MHDDV Failure Rate
1999	0.0%	0.0%	2010	0.0%	0.0%
1998	0.0%	0.0%	2009	0.0%	0.0%
1997	2.0%	2.0%	2008	2.0%	2.0%
1996	4.0%	4.0%	2007	4.0%	4.0%
1995	6.1%	6.1%	2006	6.1%	6.1%
1994	8.1%	8.1%	2005	8.1%	8.1%
1993	10.1%	10.1%	2004	10.1%	10.1%
1992	12.1%	12.1%	2003	12.1%	12.1%
1991	14.1%	14.1%	2002	14.1%	14.1%
1990	18.6%	12.7%	2001	16.1%	16.1%
1989	22.4%	15.4%	2000	18.1%	18.1%
1988	25.8%	17.8%	1999	20.2%	20.2%
1987	29.0%	20.0%	1998	22.2%	22.2%
1986	32.0%	22.0%	1997	24.2%	24.2%
1985	34.7%	23.9%	1996	26.2%	26.2%
1984	37.3%	25.7%	1995	28.2%	28.2%
1983	39.7%	27.4%	1994	30.2%	30.2%
1982	41.9%	29.0%	1993	32.2%	32.2%
1981	44.1%	30.5%	1992	34.3%	34.3%
1980	46.1%	31.9%	1991	36.3%	36.3%
1979	48.1%	33.3%	1990	48.1%	33.3%
1978	49.9%	34.5%	1989	49.9%	34.5%
1977	51.7%	35.8%	1988	51.7%	35.8%
1976	53.4%	37.0%	1987	53.4%	37.0%
1975	55.0%	38.1%	1986	55.0%	38.1%
1974	56.5%	39.2%	1985	56.5%	39.2%
1973	58.0%	40.2%	1984	58.0%	40.2%
1972	59.5%	41.2%	1983	59.5%	41.2%
1971	60.9%	42.2%	1982	60.9%	42.2%
1970	62.2%	43.1%	1981	62.2%	43.1%
1969	63.5%	44.0%	1980	63.5%	44.0%
1968	64.8%	44.9%	1979	64.8%	44.9%
1967	66.0%	45.8%	1978	66.0%	45.8%
1966	67.2%	46.6%	1977	67.2%	46.6%
1965	68.3%	47.4%	1976	68.3%	47.4%

FIGURE 6-15

PREDICTED FAILURE RATES FOR 1999 EVALUATION YEAR

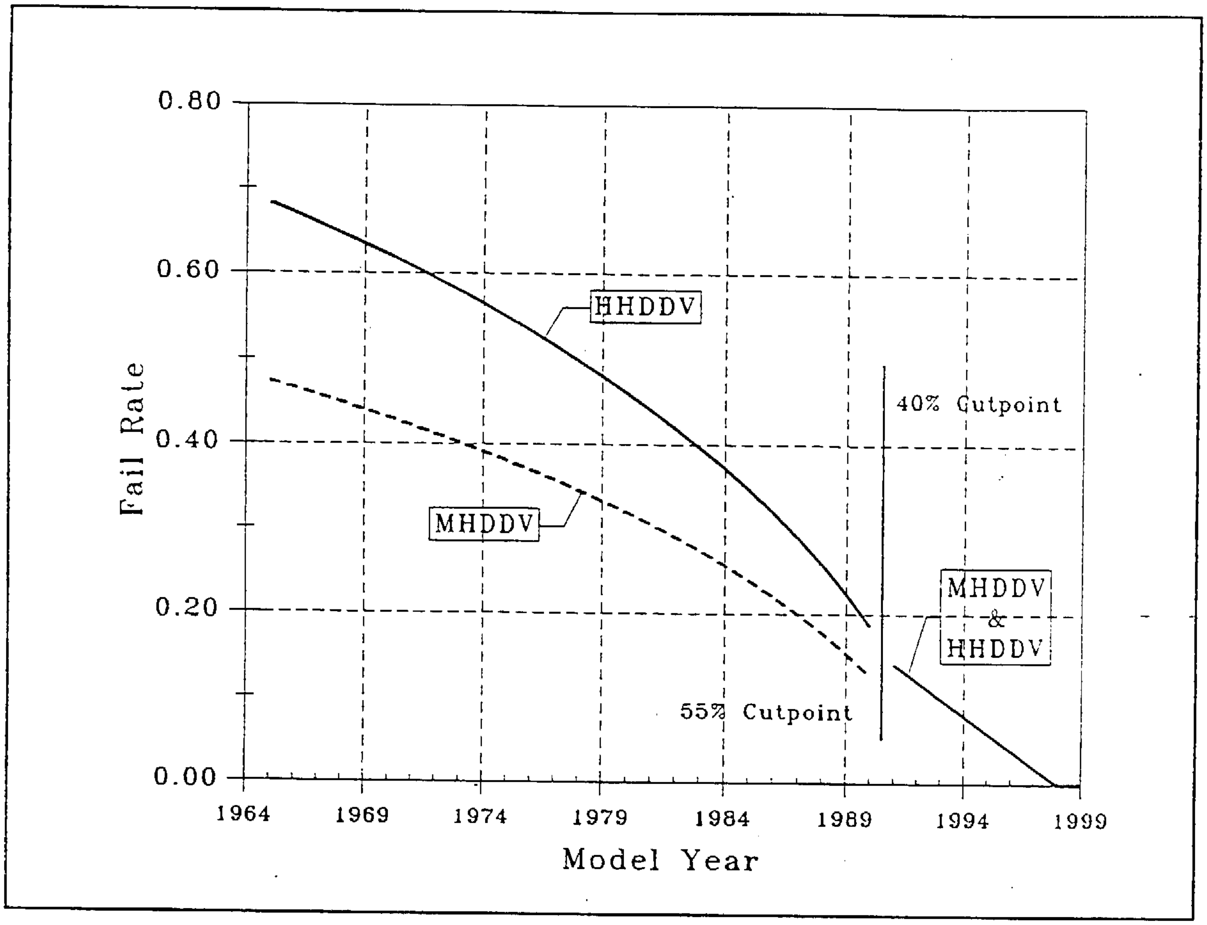
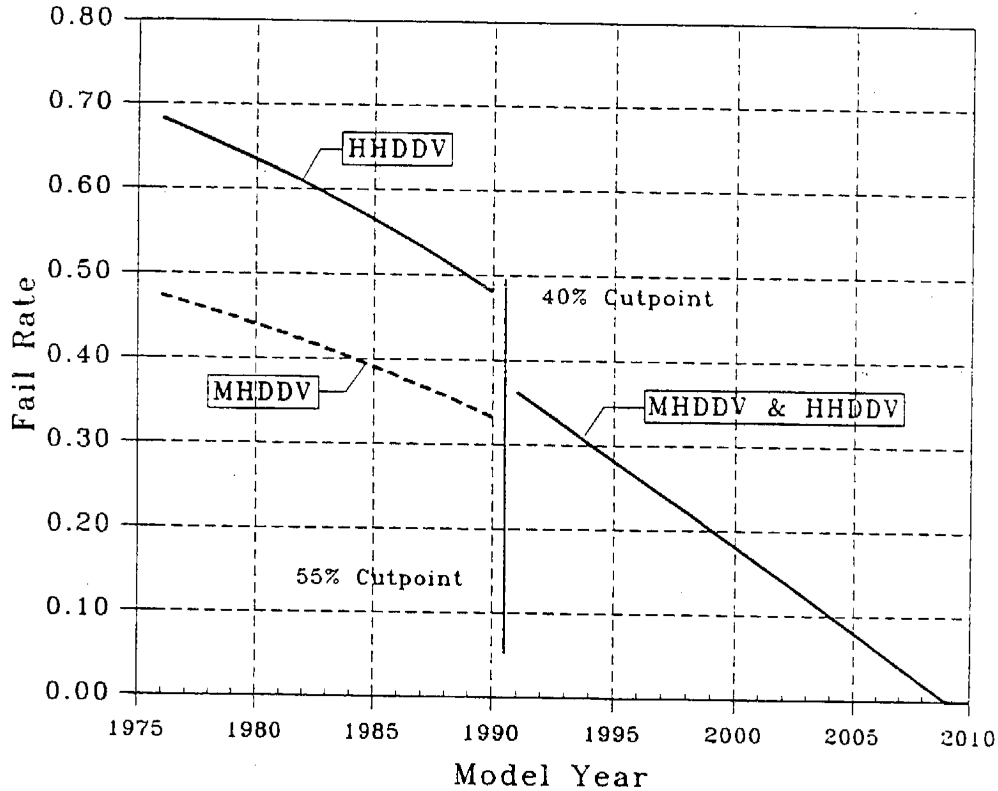


FIGURE 6-16

PREDICTED FAILURE RATES FOR 2010 EVALUATION YEAR



An estimated 291,387 inspections will be performed in 1999 and an estimated 396,939 inspections will be performed in 2010 under the PSIP. The ARB MVEI7G emissions inventory model indicates that 570,561 heavy-duty diesel vehicles will be in operation in California in 1999 and 777,214 heavy-duty diesel vehicles will be in operation in 2010. Given these estimates, there is a 7.0 percent probability of any one vehicle being inspected under the HDVIP program in 1999 and a 5.1 percent probability in 2010 (the probability declines over time since ARB staffing does not change while the total vehicle population increases). Assuming that fleet and non-fleet vehicles have an equal probability of inspection, approximately 20,429 fleet vehicles will be inspected under both the HDVIP and PSIP in 1999 and 2010. (This dual inspection of fleet vehicles can serve as an effective PSIP compliance check upon implementation of a proper fleet vehicle tracking system.) Therefore, the number of individual vehicles inspected net of HDVIP and PSIP overlap is estimated to be 310,968 (40,000+291,397-20,429) in 1999 and 416,510 (40,000+396,939-20,429) in 2010, indicating a net inspection rate of 54.5 percent of heavy-duty diesel vehicles in 1999 and 53.6 percent of heavy-duty diesel vehicles in 2010.

The overall MVEI7G heavy-duty diesel vehicle populations can be distributed across component vehicle types (light-heavy-duty, medium-heavy-duty, heavy-heavy-duty, and urban transit bus) using MVEI7G vehicle type and model year distribution functions. Applying the vehicle inspection rate as determined above and the model year-specific expected failure rates presented in Table 6-6 to the model year and vehicle class-specific populations yields estimated program failure populations. For light-heavy-duty diesel vehicles, which were not included in the Random Truck Opacity Survey used to derive expected HDVIP and PSIP failure rates, the expected failure rate is taken as one-third that of medium-heavy-duty diesel vehicles based on default MVEI7G smoke program relationships. This calculation yields estimated fleet average failure rates of 13.1 percent in 1999 and 9.2 percent in 2010.

The estimated failures rates are assumed to apply equally to both the HDVIP and PSIP. While there are intuitive reasons to think that (in the aggregate) fleet vehicles might perform differently than non-fleet vehicles due to such issues as more frequent maintenance, it must be recognized that the Random Truck Opacity Survey was based on the random selection of heavy-duty diesel vehicles for smoke measurement and includes both fleet and non-fleet vehicles, presumably in proportion to the respective populations of each on California roadways. Therefore, statistics derived through analysis of the Random Truck Opacity Survey database reflect the aggregate behavior of fleet and non-fleet vehicles and can be applied to overall California heavy-duty diesel populations without quantification of fleet/non-fleet differentials.

For 1999, the failure rate calculation requires no further adjustment since the current absence of active smoke program enforcement will not induce additional deterrence-driven heavy-duty diesel vehicle repair. However, for 2010 an adjustment is required to account for the fact that implementation of the proposed HDVIP and PSIP will influence the failure rate of heavy-duty diesel vehicles between 1999 and 2010 through the renewal of deterrence-driven vehicle repair. An estimate of the size of the necessary adjustment for 2010 can be derived using data from the original HDVIP program.

Between 1991 and 1993, the failure rate under the original HDVIP declined from 44.7 percent to 18.5 percent as a result of improved vehicle maintenance. While it is possible that this failure rate would have continued to decline before stabilizing (at a level where deteriorating vehicles offset the annual effects of improved maintenance), there is reason to believe that any continued decline would have been modest. The 1990 TSD estimated that stabilization would not occur until the fifth year of the program, however, the expected failure rate after two program years had declined by 88 percent of the total five-year expected decline. Moreover, the observed failure rate of the first year of the original HDVIP was virtually identical to that estimated in the

1990 TSD (44.7 percent versus 44.0 percent) while the observed failure rate entering the third year of the original HDVIP program (18.5 percent) was already less than the 1990 TSD's expected fifth year stabilization rate (21.2 percent). It seems reasonable to view the stabilization period as significantly shorter than estimated in the 1990 TSD and that the beginning-year and ending year-observations of the original HDVIP serve as a reasonable estimate of the magnitude of the stabilization effect.

The failure rates for 1999, combined with vehicle distribution data from the ARB's MVEI7G emission factor model yield estimated fleet-average failure rates of 13.1 percent for all heavy-duty diesel vehicles and 20.0 percent for the pre-1993 model year segment (that would have been covered by the original HDVIP at the time of its suspension.) While the test procedures for the proposed and original HDVIP are different (SAE J1667 versus SAE J1243), the overall stringency of the two programs is equivalent and each would be expected to detect the same population of excess opacity vehicles. (In fact, the SAE J1667 procedure measures smoke at an average of approximately 5 opacity-points less than the SAE J1243 procedure, but this decrease in "stringency" is offset by an equal increase in pre-1993 heavy-duty diesel vehicle smoke levels due to fleet aging.)

The estimated 20.0 percent failure rate for pre-1993 heavy-duty diesel vehicles implies that only limited backsliding of maintenance practices has occurred since the suspension of the original HDVIP at the end of 1993 (when the observed failure rate for pre-1993 vehicles was 18.5 percent). While a substantial maintenance improvement, due to implementation of the original HDVIP is still evident (since the observed failure rate during the first year of the original HDVIP was 44.7 percent), further eroding of this improvement can be expected in the absence of implementation of the proposed HDVIP and PSIP. Based on the 18.5 percent failure rate at the end of the original HDVIP and the 20.0 percent failure rate for an equivalent vehicle population in the Random Truck Opacity Survey, it is reasonable to expect a 7 percent decline in future year failure rates under the proposed HDVIP program (relative to the failure rates forecast using the Random Truck Opacity Survey database). Applying this factor to the estimated 2010 failure populations presented in Table 6-6 provides an estimate of the stabilized failure populations that can be expected to be observed in that year. This adjustment reduces the expected HDVIP and PSIP failure rate in 2010 from 9.2 percent to 8.6 percent.

Observations from the original HDVIP also provide a good indication of the fraction of failed vehicles that will be repaired under the proposed HDVIP and PSIP. Under the original program, 8,493 repair citations were issued. Of these, 392 are still pending, yielding a net of 8,101 citations that are not currently under review. Of these citations 6,356 have been cleared, implying a 78.5 percent repair rate for vehicles cited. This again agrees remarkably well with the 79.1 percent overall repair rate estimated in the 1990 TSD. As a result, the 78.5 percent observed repair rate from the original HDVIP is taken to be a valid estimate of the expected repair rate under the proposed HDVIP and PSIP.

Combining these factors yields an estimate of 31,859 repaired heavy-duty diesel vehicles in 1999 and 27,941 repaired heavy-duty diesel vehicles in 2010. Chapter 5 presents the estimated average costs of model year-specific repairs necessary to bring vehicles into compliance with proposed HDVIP and PSIP standards. When these costs are weighted in accordance with expected failure populations, the aggregate per-vehicle repair cost is estimated to be $664 in 1999 and $581 in 2010. Therefore, the overall cost of vehicle repair is estimated to be $21.16 million in 1999 and $16.23 million in 2010. Table 6-7 presents a summary of the derivation of these estimates.

TABLE 6-7

ESTIMATED FAILED VEHICLE REPAIR COSTS[1]

	1999	2010
Vehicles Subject to HDVIP and PSIP	570,561	777,214
Aggregate HDVIP and PSIP Inspection Rate	0.5450	0.5359
Aggregate HDVIP and PSIP Failure Rate	0.1306	0.0855
HDVIP and PSIP Repair Rate	0.7846	0.7846
Failures Repaired Under the HDVIP and PSIP	31,859	27,941
Average Cost of Repair	$664	$581
Total Failed Vehicle Repair Cost	**$21,162,379**	**$16,229,616**

1 Totals do not exactly match component calculations due to rounding.

6.5.2 Costs of Improved Vehicle Maintenance

A substantial number of vehicles will be voluntarily repaired in response to HDVIP and PSIP implementation due to the threat of inspection and citation issuance. Historically, significant reductions in excess emissions have been observed due to this deterrence effect upon implementation of similar programs (e.g., vehicle inspection programs for light-duty vehicles). The 1990 TSD asserted that this same phenomena was likely to be observed upon implementation of the original HDVIP. Data collected during the two years that program was in operation confirm this assertion.

In the first two years of the original HDVIP, the observed failure rate declined by nearly 58 percent, validating the expectation of a substantial deterrence effect (since less than 10 percent of the heavy-duty diesel vehicles in operation in California had actually been inspected under the original HDVIP). This reduction in combination with the total number of vehicles inspected in the original HDVIP implies that approximately 26 percent of heavy-duty diesel vehicles were subjected to successful deterrence-driven repairs due to original HDVIP implementation. Data from the recent Random Truck Opacity Survey suggests that this deterrence effect has regressed by about 8 percent since the suspension of the original HDVIP program at the end of 1993 (see Section 6.5.1 above), but a significant effect is still evident. Based on the observed Random Truck Opacity Survey results and data from the original HDVIP it appears that over 24 percent of heavy-duty diesel vehicles will be subjected to deterrence-based repairs during the first year of proposed HDVIP and PSIP implementation and further, that this deterrence effect will rise to approximately 26 percent in subsequent program years (as the losses due to backsliding since 1993 are reclaimed).

Estimating the cost of this deterrence effect is problematic. First, some of the benefit is derived from avoided tampering, an occurrence that results in no net cost to vehicle owners. Second, it is very likely that those vehicles with minor problems will be preferentially maintained since it is this population for which the threat of a $300 citation penalty poses the greatest risk (for vehicles requiring greater repairs, the risk-adjusted value of receiving a citation could be more cost-effective than the actual repairs). Finally, the issue of repair lifetime must be considered. Certainly 26 percent of malmaintained vehicles are not repaired annually (although there is an initial "spike" in repairs during the initial years of smoke program enforcement; this "spike" has already occurred in California due to the original HDVIP). This instead represents the cumulative fraction of vehicles repaired before a steady-state condition is achieved wherein the annual deterrence-driven repair impact of vehicles is just offset by an equal (but opposite) emissions increase from deteriorating vehicles.

For this analysis, it was assumed that all deterrence effects are achieved through actual vehicle repair (i.e., no vehicle owners are assumed to simply avoid tampering or to restore previously-tampered items at no cost), and that the average cost of deterrence-driven repairs is equal to the average cost of failure-based repairs (i.e., deterrence-driven repairs are <u>not</u> assumed to be cheaper on average than failure-driven repairs). These assumptions should maximize the cost of deterrence-based vehicle repair and, therefore, yield a conservative estimate of HDVIP- and PSIP-driven impacts. The stabilized annual fraction of vehicle owners performing deterrence-based repairs is equal to the differential between the estimated future failure rates with and without the deterrence effect considered.

Based on these assumptions, a total of 3,413 heavy-duty diesel vehicles in 1999 and 5,074 heavy-duty diesel vehicles in 2010 are expected to perform deterrence-driven repair in direct response to implementation of the proposed HDVIP and PSIP. Combining these estimates with the average per-vehicle estimated repair costs of $664 in 1999 and $581 in 2010 yields estimates for the deterrence-based cost of vehicle repair of $2.27 million in 1999 and $2.95 million in 2010.

6.5.3 Indirect Program Costs

In addition to the vehicle repair and citation penalty costs described above, vehicle owners will also be subjected to a lost opportunity cost equal to the value of vehicle and driver out-of-service time. For the PSIP, it is assumed that both inspections and any necessary repairs will be accomplished during the normal out-of-service period for subject vehicles. As a result, no opportunity costs are incurred under the PSIP. For the proposed HDVIP, the same assumptions used in the 1990 TSD are used to estimate costs as follows:

- Weighted average repair time is 1.03 days;
- The average out-of-service time for a failed inspection is 15 minutes;
- The average out-of-service time for a passed inspection is 3 minutes;
- The average driver out-of-service time for a repair is 2 hours.

For the proposed HDVIP opportunity cost estimate, the weighted average daily capital charge for heavy-duty diesel vehicles has been increased from the $70 per day value used for the original HDVIP TSD to $100 per day. Similarly, the fully-burdened labor rate for heavy-duty diesel vehicle drivers has been increased from $19 per hour to $25 per hour. Combining these assumptions with the vehicle inspection, failure, and repair estimates presented in the preceding subsections yields an estimated lost driver-time opportunity cost of $0.30 million in 1999 and $0.22 million in 2010 and an estimated lost vehicle-time opportunity cost of $0.48 million in 1999 and $0.34 million in 2010. The total lost opportunity cost is estimated to be $0.77 million in 1999 and $0.57 million in 2010.

6.5.4 Cost of Reduced Fuel Consumption

Repairs undertaken to reduce heavy-duty diesel vehicle smoke (either through failure of the HDVIP or PSIP or through the deterrence effects of the programs) will impact heavy-duty diesel vehicle fuel consumption in California. This impact accrues as a direct cost to heavy-duty diesel vehicle owners and must be accounted for in determining overall program costs.

Section 7.4 presents an estimate of the magnitude of this fuel consumption impact. Based on the same malperformance model used to estimate criteria pollutant impacts, a decrease of 0.69 percent in heavy-duty diesel vehicle fuel consumption is estimated in 1999 and, similarly, of 0.66 percent in 2010 due to HDVIP and PSIP implementation. Using the fuel-consumption estimates forecast by the MVEI7G model for those years, these percentages translate into a net diesel fuel savings of 16.74 million gallons in 1999 and 19.22 million gallons in 2010. Assuming a $1.30 per gallon cost of diesel fuel yields estimates of a net savings of $21.76 million in 1999 and $24.98 million in 2010 due to repair-driven decreases in heavy-duty diesel vehicle fuel consumption.

6.6 TOTAL PROGRAM COSTS

Section 6.3 presents estimates of total HDVIP and PSIP labor and administration costs in both 1999 (the first full year of program implementation) and 2010. Section 6.5 presents costs incurred by the regulated industry due to vehicle inspection, repair and reduced fuel consumption. Table 6-8 summarizes these estimated HDVIP and PSIP costs. As indicated, the annual cost to California is estimated to be $22.37 million in 1999, dropping to $20.20 million in 2010.

TABLE 6-8

SUMMARY OF HDVIP AND PSIP COSTS

	1999	2010
Administrative Cost to Fleets		
Annual Labor Cost (PSIP)	$1,255,761	$1,642,385
Annual Capital Cost for Smokemeters (PSIP)	$5,005,009	$6,817,787
Annual Cost of Contractual PSIP Inspections (PSIP)	$10,725,351	$14,027,474
Total Fleet Annual Administrative Cost	$16,986,121	$22,487,646
Costs to Vehicle Owners		
Annual Repair Cost (HDVIP + PSIP)	$21,162,379	$16,229,616
Annual Increased Maintenance Cost (HDVIP + PSIP)	$2,267,097	$2,947,141
Annual Lost Opportunity Cost of Time (HDVIP)	$771,936	$567,603
Annual Cost of Fuel (HDVIP + PSIP)	($21,764,145)	($24,983,116)
Total Cost to Vehicle Owners	$2,437,267	($5,238,756)
Total HDVIP and PSIP Cost		
Total Program Cost	$19,423,388	$17,248,890

CHAPTER 7
BENEFITS OF THE HDVIP AND PSIP

7.1 OVERVIEW

As with the cost analysis, the emissions impact analysis in this report evaluates the impact of the overall inspection programs compared to having no such programs. The Staff Report also includes an incremental analysis showing the impact of the programs with the proposed amendments incorporated, compared to the originally-adopted programs.

Implementation of the HDVIP and PSIP will produce a series of benefits that can be generally classified as follows:

- A reduction in the number of heavy-duty diesel vehicles emitting excessive smoke;
- A reduction in criteria and toxic air pollutant emissions from heavy-duty diesel vehicles;
- A reduction in heavy-duty diesel vehicle fuel consumption;
- A potential improvement in heavy-duty diesel vehicle reliability and performance.

Reducing the number of excessively-smoking heavy-duty diesel vehicles is the primary goal of the HDVIP and PSIP. Reductions in criteria and toxic air pollutants, reductions in fuel consumption, and any improvements in vehicle reliability and performance accrue as direct, but secondary, benefits of the smoke reduction repairs.

This chapter presents estimates of the magnitude of reductions of excessive smoke, criteria pollutants (i.e., hydrocarbons or ROG, NOx and PM), and fuel consumption that will accrue due to HDVIP and PSIP implementation. Estimates have not been developed for toxic air pollutant reductions or any heavy-duty diesel vehicle reliability and performance improvements arising out of program implementation, primarily due to a lack of definitive data on which to quantify the magnitude of such benefits. Studies necessary to determine the magnitude of toxic air pollutant reduction and vehicle performance benefits could be conducted as an integral component of the HDVIP and PSIP programs simultaneously with active program enforcement. As demonstrated below, the HDVIP and PSIP are very cost-effective programs, even in the absence of explicit estimates for these secondary program benefits.

Section 7.2 presents estimates for the HDVIP- and PSIP-driven reduction in the number of excessively-smoking heavy-duty diesel vehicles operating in California. Section 7.3 presents estimates of program-driven reductions in criteria pollutant emissions. Finally, Section 7.3 presents estimates for the quantity of diesel fuel saved due to HDVIP and PSIP implementation.

7.2 REDUCTION IN THE NUMBER OF VEHICLES EMITTING EXCESSIVE SMOKE

Generally, the effectiveness of an emissions control program is measured in terms of dollar cost per mass of pollutant reduced. However, since the primary goal of the HDVIP and PSIP is to reduce the level of smoke emissions from heavy-duty diesel vehicles, such a metric is of no utility in quantifying primary program benefits. Smoke emissions are not measured on a mass basis and cannot be added across all operating heavy-duty diesel vehicles to provide a useful measure of the total quantity of smoke reduced through the HDVIP and PSIP. The most reasonable measure for evaluating HDVIP and PSIP success in reducing smoke emissions is through an estimate of the program-induced decrease in the number of heavy-duty diesel vehicles with excessive smoke emissions operating in California.

The 1990 TSD presented a detailed theoretical analysis of the expected reduction in the number of heavy-duty diesel vehicles with excessive smoke emissions operating in California between 1990 and 1995 due to the implementation of the original HDVIP. While the details of that analysis are not reproduced here, a decline in the fraction of excessively-smoking vehicles from 44 percent of the heavy-duty diesel fleet in 1990 to 21 percent of the fleet in 1995 was predicted. Section 6.5.2 of this TSD discusses data collected under the original HDVIP that provides a compelling validation of the 1990 TSD's analysis. Moreover, this observational data provides a firm foundation on which to base the expected decline in excessive smoke emissions due to implementation of the proposed HDVIP and PSIP.

Data from the original HDVIP indicates that approximately 45 percent of heavy-duty diesel vehicles were emitting excessive smoke during the first few months of the program in 1991. By the end of 1993, this fraction had declined to 18.5 percent, readily illustrating the effectiveness of that program in reducing the number of vehicles with excessive smoke emissions. The recent Random Truck Opacity Survey, conducted in support of the proposed HDVIP and PSIP, indicates that the current failure rate for the same subset of vehicles subject to the original HDVIP (i.e., pre-1993 model year heavy-duty diesel vehicles) is approximately 20 percent (for an equivalent-stringency opacity standard and adjusting for fleet aging). Therefore, while there apparently has been some backsliding of maintenance practices since the suspension of the original HDVIP, the effects of that program remain strong and the number of heavy-duty diesel vehicles emitting excessive smoke continues to be well below that which would be observed if the program were never implemented. It seems reasonable, however, to expect that over time, the percentage of heavy-duty diesel vehicles with excessive smoke emissions will continue to increase if the proposed HDVIP and PSIP are not implemented, eventually stabilizing at a level near that observed at the beginning of the original HDVIP.

In addition to preserving the current gains made through the implementation of the original HDVIP, implementation of the proposed HDVIP and PSIP will promote a renewed emphasis on vehicle maintenance and a corresponding further reduction in the number of excessively-smoking vehicles in California. It is estimated that after the first full year of implementation of the proposed HDVIP and PSIP (i.e., 1999), an additional 7 percent decline in the number of excessively-smoking heavy-duty diesel vehicles will be observed through the renewed promotion of deterrence-based vehicle maintenance (returning such maintenance practice to the same rate of occurrence as observed at the time of suspension of the original HDVIP and avoiding further erosion of the gains of that program). This translates into a estimated 70,472 excessively-smoking heavy-duty diesel vehicles in California in 1999 as opposed to 74,503 in the State without the proposed HDVIP and PSIP. Similarly, the number of excessively-smoking heavy-duty diesel vehicles in California in 2010 is estimated to be 67,657 with the proposed HDVIP and PSIP and 71,526 without the programs.

These reductions should be viewed in a larger perspective in that the indicated decline in excessively-smoking heavy-duty diesel vehicles (4,030 vehicles in 1999 and 3,869 vehicles in 2010) is but a fraction of the total decline due to HDVIP and PSIP implementation. In the absence of the lingering deterrence effects of the original HDVIP an additional 24,747 excessively-smoking heavy-duty diesel vehicles would be in operation in 1999 and an additional 33,710 excessively-smoking heavy-duty diesel vehicles would be in operation in 2010. Therefore, the overall reduction in excessively-smoking heavy-duty diesel vehicles is 28,778 in 1999 and 37,580 in 2010. These reductions equate to a 29 percent reduction in excessively-smoking trucks in 1999 and a corresponding 36 percent reduction in 2010. While the bulk of the original HDVIP-driven share of the reduction for 1999 can be presumed to occur regardless of implementation of the proposed HDVIP and PSIP (given the fact that most of the deterrence-driven reduction is currently in place), there is no assurance that the estimated reduction for 2010 would not erode substantially if enforcement of smoke standards is not resumed. Between 1999 and 2010, much, if not all of the lingering deterrence effect of the original HDVIP could be lost without implementation of the proposed HDVIP and PSIP.

7.3 REDUCTION IN CRITERIA POLLUTANT EMISSIONS

Repairs and deterrence effects of the HDVIP and PSIP will not only reduce the number of vehicles with excessive smoke emissions, but will also reduce mass emissions of criteria pollutants. However, the determination of HDVIP and PSIP impacts on criteria pollutant emissions is complex, involving such factors as detailed data on emission control system malperformance, the effect of individual malperformances on criteria pollutant emissions, the ability of the HDVIP and PSIP to identify individual malperformances, and the success of vehicle repairs in correcting identified malperformances. This subsection presents an estimate of these factors and the resulting magnitude of the criteria pollutant impact for ROG, NO_x, and PM. CO emissions from diesel vehicles are low relative to their gasoline counterparts (due to excess air combustion conditions) and therefore are not addressed in this analysis. The ARB MVEI7G emissions inventory model indicates that diesels in total are responsible for only about 3.5 percent of vehicular CO emissions in 1999 and about 7.5 percent of vehicular CO emissions in 2010.

Subsequent to the preparation of the 1990 TSD, the ARB updated their MVEI7G emissions inventory model to estimate the criteria pollutant impacts of a heavy-duty diesel vehicle smoke inspection program such as that proposed. Using the MVEI7G model would greatly simplify the determination of criteria pollutant emission impacts since the model represents the State's official emissions inventory estimation tool and would provide a direct link between the analysis of HDVIP and PSIP emission reductions and the overall State emissions inventory. Moreover, since ARB modeling staff indicates that the encoded MVEI7G algorithm to estimate emission reduction impacts was based on the methodology outlined in the 1990 TSD, the theoretical foundation for the algorithm is both documented and well understood.

Unfortunately, preliminary emissions analyses using MVEI7G indicated problems with practical application of the model algorithm. First, the model did not account for the deterrence effects of the smoke inspection program, instead assuming that only those vehicles that are actually inspected and issued citation make any repairs. As experience with both light duty vehicle inspection programs and the original HDVIP indicate, there is a sizeable deterrence effect due to program implementation that must be accounted for in quantifying program benefits. Second, the MVEI7G model-assumed failure rate for individual model year vehicles is invariant over time. For example, a 1990 model year vehicle fails at the same rate in 2010 (when it is 20 years old) as it did in 1995 (when it was 5 years old). Such an assumption is not consistent with test program data such as that discussed in Section 6.4. Finally, the pollutant-specific impact coefficients encoded in MVEI7G are not consistent with the 1990 TSD modeling upon which the MVEI7G algorithm was based. In fact, individual repairs would have to reduce emissions by more than 100 percent in some cases for the coefficients encoded in MVEI7G to be accurate.

To surmount these issues while at the same time retaining the advantages of MVEI7G in terms of overall consistency with the State inventory (including consistency of overall vehicle counts, model year distributions, and vehicle class distributions), alternative sets of input parameters for use in the MVEI7G emissions impact algorithm were developed to properly consider all HDVIP and PSIP impacts. The MVEI7G algorithm can effectively recognize five distinct HDVIP- and PSIP-related parameters as follows:

- The calendar year-specific heavy-duty diesel vehicle inspection rate;
- The model year-specific failure rate within each class of heavy-duty diesel vehicles;
- The calendar year-specific failed vehicle repair rate;
- Model year- and pollutant-specific (ROG, NO_x, and PM) emissions impact factors;
- A calendar year-specific "discount" factor to correct for the phase-in of program benefits during initial inspection years.

Revised data was developed for each of these five parameters for both 1999 and 2010 to analyze HDVIP and PSIP benefits.

7.3.1 Pollutant-Specific Emissions Impact Factors

As indicated above, the pollutant-specific emissions impact factors encoded in the MVEI7G model imply a greater than 100 percent emission reduction effectiveness of repair in some cases. Therefore, these factors were revised for this analysis to better reflect the actual emission reduction benefits of vehicle repair. The basic smoke program-induced correction algorithm encoded in MVEI7G is:

$$\text{BER CF}_{ijk} = \left(\frac{IR_i}{100}\right)\left(\frac{RR_i}{100}\right)\left[\left(\frac{1}{1 + \left(\frac{FR_{ij}}{100}\right)\left(\frac{PSIF_{ijk}}{100}\right)}\right) - 1\right] + 1$$

where: BER CF is the basic emission rate correction factor for vehicle class "i", model year "j", and pollutant "k" due to smoke program implementation,

IR is the smoke program inspection rate for vehicles in class "I" in the calendar year being modeled (in percent),

RR is the fraction of failed vehicles in class "I" repaired in the calendar year being modeled (in percent),

FR is the smoke program failure rate for vehicle class "I" and model year "j" (in percent), and

PSIF is the emissions impact of repairs for vehicle class "I" and model year "j" on pollutant "k" (in percent).

The structure of this algorithm is quite complex, especially the term involving the inverse of the failure rate (FR) and pollutant-specific impact factor (PSIF). Nevertheless, the basic emission rate correction factor (BER CF) should be equivalent to a calculation based on a simple pollutant mass balance as follows:

$$\begin{aligned}\text{BER CF} &= (\text{Fraction Not Repaired})(1) + (\text{Fraction Repaired})(\text{ERCF}) \\ &= (1 - \text{Fraction Repaired}) + (\text{Fraction Repaired})(\text{ERCF}) \\ &= 1 - \left(\frac{IR}{100}\right)\left(\frac{FR}{100}\right)\left(\frac{RR}{100}\right) + \left(\frac{IR}{100}\right)\left(\frac{FR}{100}\right)\left(\frac{RR}{100}\right)(\text{ERCF})\end{aligned}$$

where: ERCF is the fraction of pre-repair emissions left after a smoke program-induced vehicle repair.

The emissions reduction correction factor (ERCF) is the parameter typically measured (or estimated) in any program investigating the effectiveness of vehicle repairs. Such an analysis was undertaken in support of the original HDVIP, the results of which were presented in the 1990 TSD. The analysis presented in that TSD continues to represent the state-of-the-art methodology for evaluating the effect of smoke program-induced repairs on criteria pollutant emissions. In fact, the parameters currently encoded in MVEI7G are presumably based on the analysis presented in that TSD. However, since the actual encoded parameters are not consistent with that analysis (or consistent with intuition since repairs of greater than 100 percent effectiveness are not possible), a re-analysis of HDVIP- and PSIP-induced repair impacts was performed.

Following a methodology identical to that described in Section 7.4 of the 1990 TSD program, the ERCF associated with smoke program-induced repairs was recalculated. Since the methodology is fully-documented in the 1990 TSD, it is not reproduced in this document. However, those portions of Section 7.4 describing the analysis methodology are incorporated herein by reference. The only exception to the identicalness of the analysis performed in support of the proposed HDVIP and PSIP and that performed for the original HDVIP is that the assumed particulate trap and oxidation catalyst technology penetration fractions were revised to more accurately reflect current and expected future practices for 1994 and newer vehicles, as presented in Table 7-1. Tables 7-2 and 7-3 present the resulting emission reduction correction factors for average and fully-successful smoke program-induced repairs[1] respectively.

The emission reduction correction factors (ERCF) presented in Tables 7-2 and 7-3 can be converted into MVEI7G-equivalent pollutant-specific impact factors (PSIF) for input into MVEI7G by equating the two expressions for the basic emission rate correction factor (BER CF) shown above. Solving the resulting expression for the pollutant-specific impact factor yields:

$$PSIF = \left(\frac{10{,}000}{FR}\right)\left[\left(\frac{1}{\left(\frac{FR}{100}\right)(ERCF) - \left(\frac{FR}{100}\right) + 1}\right) - 1\right]$$

Using this relationship, the emission reduction correction factor values presented in Tables 7-2 and 7-3 can be readily converted into an equivalent pollutant-specific impact factor value for any given HDVIP and PSIP failure rate.

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[1] The impacts of "average" repairs incorporate the emission reduction effects of a proper repair, but also consider the percentage of time the needed repair is either not properly diagnosed or is malperformed. In contrast, a "fully-successful" repair assumes that a proper diagnosis and repair is always made (and, therefore, reflects maximum emission impacts).

TABLE 7-1

CATALYST AND PARTICULATE TRAP DEFECT FREQUENCIES

Defect	Vehicle Class	Frequency of Occurrence in the 1990 TSD	Frequency of Occurrence for HDVIP and PSIP Analysis
Catalyst Removed	HHDDV	0.00	0.00
	MHDDV	0.00	0.01
	LHDDV	0.00	0.03
	Urban Bus	0.00	0.00
Trap Removed	HHDDV	0.40 / 0.50[1]	0.00
	MHDDV	0.30	0.00
	LHDDV	0.30	0.00
	Urban Bus	0.05	0.00

[1] California-certified engines / Federally-certified engines.

TABLE 7-2

EMISSION REDUCTION CORRECTIONS FOR AVERAGE REPAIRS

Vehicle Class	Model Years	ROG	NO_x	PM
HHDDV	Pre-1987	0.8211	0.9817	0.6411
	1988-1990	0.8349	0.9869	0.6798
	1991-1993	0.7952	1.0008	0.7123
	1994 and Later	0.8046	1.0008	0.6755
MHDDV	Pre-1987	0.8171	0.9934	0.6650
	1988-1990	0.8258	0.9967	0.6990
	1991-1993	0.7464	1.0037	0.6693
	1994 and Later	0.7549	1.0037	0.6243
LHDDV	Pre-1987	0.8432	0.9926	0.7492
	1988-1990	0.8442	0.9939	0.7514
	1991-1993	0.7542	1.0007	0.6772
	1994 and Later	0.7627	1.0007	0.6388
Urban Bus	Pre-1987	0.8914	1.0021	0.8063
	1988-1990	0.9254	1.0041	0.8716
	1991-1993	0.8768	1.0024	0.7887
	1994 and Later	0.8784	1.0024	0.7906

TABLE 7-3

EMISSION REDUCTION CORRECTIONS FOR FULL REPAIRS

Vehicle Class	Model Years	ROG	NO_x	PM
HHDDV	Pre-1987	0.5879	0.9450	0.4257
	1988-1990	0.6201	0.9086	0.4625
	1991-1993	0.5518	0.8488	0.3923
	1994 and Later	0.5482	0.8488	0.2965
MHDDV	Pre-1987	0.5407	0.9309	0.4268
	1988-1990	0.5562	0.9280	0.4552
	1991-1993	0.4376	0.9004	0.3249
	1994 and Later	0.4324	0.8919	0.2173
LHDDV	Pre-1987	0.5474	0.9996	0.5116
	1988-1990	0.5477	0.9908	0.5117
	1991-1993	0.4221	0.9083	0.3278
	1994 and Later	0.4163	0.8961	0.2154
Urban Bus	Pre-1987	0.6761	0.9545	0.5882
	1988-1990	0.7457	0.9885	0.6886
	1991-1993	0.6606	0.9741	0.4514
	1994 and Later	0.6520	0.9741	0.4474

7.3.2 Vehicle Inspection Rate

Conceptually, quantifying the inspection rate for the HDVIP and PSIP is a straightforward calculation of the ratio of the number of vehicles inspected to the number of vehicles in use. However, because the smoke inspection program correction factor algorithm encoded in the ARB MVEI7G emissions inventory model is fairly simplistic and does not incorporate any explicit mechanism for considering the deterrence-driven maintenance impacts of the HDVIP and PSIP, these impacts must be modeled using the standard "inspection-failure-repair" algorithm presented above. Effectively, the impacts of any smoke inspection program can be broken down into two basic components: (1) the impacts of repairs resulting from actual inspection failure and (2) the impacts of deterred tampering and preventive maintenance undertaken to minimize failure risk. The former impacts are limited by the actual number of vehicles inspected while the latter impacts affect a far greater vehicle population. Therefore, a simple encoding of the fundamental HDVIP and PSIP inspection rate into the MVEI7G model will significantly underestimate overall program impacts.

As discussed in Section 6.5.2, approximately 26 percent of heavy-duty diesel vehicles are expected to exhibit reduced emissions due to either deterred tampering or increased maintenance. This estimate is based on actual smoke inspection program experience in California, gleaned from original HDVIP data collected between 1991 and 1993. As stated in Section 6.5.2, this deterrence effect was originally hypothesized in the 1990 TSD and has subsequently been effectively confirmed in actual practice through the original HDVIP.

Since the MVEI7G smoke inspection correction factor algorithm does not include an explicit mechanism to address this deterrence fraction, it must be modeled through its equivalent impact on the effective vehicle inspection rate. This rate significantly exceeds the actual inspection rate calculated strictly on the basis of physical inspections performed. The effective inspection rate can be alternatively viewed as that rate of inspection that would bring about the same improved maintenance behavior in a fleet of vehicles that undertook no improved maintenance except in instances of smoke inspection failure.

7.3.3 Vehicle Failure Rate

As was the case with the vehicle inspection rate, quantifying the basic vehicle failure rate for the HDVIP and PSIP is a conceptually straightforward calculation of the ratio of the number of vehicles failed to the number of vehicles inspected. However, the deterrence effect that affects the vehicle inspection rate, as described in Section 7.3.2, carries over to affect the failure rate calculation as well. In effect, 100 percent of vehicles undertaking deterrence-based maintenance are assumed equivalent to inspection "failures". Therefore, the effective HDVIP and PSIP failure rate is the effective inspection population-weighted average of the 1999 and 2010 model year and class-specific failure rates presented in Table 6-6, and an effective failure rate of 100 percent for deterrence-driven repairs. Light-heavy-duty diesel vehicle failure rates have been estimated by adjusting the medium-heavy-duty failure rates presented in Table 6-6 by a factor of one-third.

This correction factor for light-heavy-duty diesel vehicles is derived from the default class-specific smoke program failure rates encoded in the MVEI7G model.

7.3.4 Failed Vehicle Repair Rate

Quantifying the basic vehicle repair rate for the HDVIP and PSIP is a conceptually straightforward calculation of the ratio of the number of vehicles repaired to the number of vehicles failed. But once again, the deterrence effect described in the Sections 7.3.2 and 7.3.3 carries over to affect the vehicle repair rate calculation. Since 100 percent of the malfunctions undertaken through deterrence-based maintenance are corrected, these vehicles exhibit both a 100 percent repair rate and an individual pollutant-specific repair impact that is greater than the aggregate impacts of average defect identification rates and average defect correction rates. The effective HDVIP and PSIP repair rate is the failed vehicle population-weighted average of the 78.5 percent repair rate for vehicles that were physically inspected and failed, as observed in the original HDVIP (and assumed for the proposed HDVIP and PSIP, see Section 6.5.1) and an effective repair rate of 100 percent for deterrence-driven maintenance. Moreover, the average and fully-successful pollutant-specific impact factors (PSIF) presented in Tables 7-2 and 7-3 must be aggregated by this same weighting factor to derive appropriate calendar year-specific PSIF values for input into MVEI7G.

7.3.5 First Year Program Benefit Discount

The MVEI7G smoke inspection program correction factor algorithm discounts first year emission reduction benefits by 50 percent and assumes zero benefit for calendar years in which no smoke inspection program is in place. While this makes intuitive sense, it is not explicitly correct for calendar years, such as 1994 through 1998, where there are residual carryover maintenance impacts associated with a previously-operating smoke program (in this case the original HDVIP). However, this is not a concern for the 1999 and 2010 emissions modeling performed in this analysis and has, therefore, not been altered. Full HDVIP and PSIP emission reduction benefits are assumed in both emissions analysis years.

7.3.6 The No HDVIP and PSIP Baseline

In the standard MVEI7G emissions inventory model, emission loads without a smoke program in place cannot be estimated in a calendar year during which a smoke program is in effect. The MVEI7G model assumes that a smoke program either is or is not in place in any given calendar year and cannot be instructed to model the same year both with and without a smoke program. To surmount this problem and derive both "with HDVIP and PSIP" and "without HDVIP and PSIP" emission estimates, a modified version of the MVEI7G smoke program parameter input table was developed that included a vehicle failure rate of zero for all vehicle classes and model years. This input table forces the basic emission rate correction factor to unity, thereby providing an estimate of uncorrected heavy-duty diesel vehicle emission rates.

7.3.7 MVEI7G-Estimated HDVIP and PSIP Emission Reductions

Appendix C presents the MVEI7G input parameter files used to model the impacts of the HDVIP and PSIP in 1999 and 2010, respectively. These input files are designed to incorporate both direct failure-driven repair impacts and impacts accruing as a result of deterrence-driven vehicle repair. The Statewide criteria pollutant emission reductions estimated by MVEI7G are presented in Table 7-4. As indicated, the HDVIP and PSIP are expected to reduce 1999-ROG emissions by 6.37 tons per average day, 1999-NO_x emissions by 12.24 tons per average day, and 1999-PM emissions by 5.23 tons per average day respectively. Similar reductions in 2010 of 5.30 tons of ROG per average day, 14.04 tons of NO_x per average day, and 3.20 tons of PM per average day are predicted. (MVEI7G predictions of tons per summer day and tons per winter day were converted to tons per average day by assuming summer emissions are applicable eight months of the year and winter emissions are applicable four months of the year. The net effect of this weighting scheme is negligible since there are no significant differences in estimated summer and winter impacts.)

The considerable difference between the MVEI7G-estimated baseline emission estimates for ROG, NO_x, and PM relative to corresponding estimates derived under the alternative methodology documented in the 1990 TSD (even after considering the impacts of fleet turnover) raises some concern that MVEI7G may not account for the full level of vehicle malperformance in determining baseline heavy-duty diesel vehicle emission rates. Nevertheless, given the standing of the MVEI7G model, the estimates presented in Table 7-4 were used without alteration to estimate HDVIP and PSIP cost effectiveness in the "dollars per pound" format commonly used to evaluate other emission control programs. Given the observed differentials between MVEI7G baseline emission estimates and corresponding estimates developed in the 1990 TSD, the derived cost effectiveness estimates should be viewed as a conservative indicator of program value.

7.4 FUEL CONSUMPTION IMPACTS

The same basic malperformance model used to estimate the impacts of smoke repairs on criteria pollutant emissions (as described in detail in Section 7.4 of the 1990 TSD) also generates a corresponding estimate of the effect of smoke repairs on diesel fuel consumption. While this impact is modest, it is nevertheless positive and does accrue as a direct result of HDVIP and PSIP implementation. Based on the population-weighted repair impacts predicted by the emissions malperformance model, a net decrease in diesel fuel consumption of 0.69 percent in 1999 and 0.66 percent in 2010 is estimated in response to HDVIP and PSIP implementation. Using the fuel consumption estimates forecast by the MVEI7G model for those years, the net diesel fuel savings expected as a result of HDVIP and PSIP implementation is 16.74 million gallons in 1999 and 19.22 million gallons in 2010.

TABLE 7-4.

HDVIP AND PSIP CRITERIA POLLUTANT REDUCTIONS

Calendar Year	Pollutant	Total On-Road Vehicle Emissions (tpd)	Total HDDV Emissions (tpd)	HDVIP and PSIP Emission Reductions (tpd)
1999	ROG	1063.97	48.66	6.37
	NO_x	1597.68	443.16	12.24
	PM	52.61	28.96	5.24
	Total	2,714.26	520.78	23.84
2010	ROG	441.09	40.33	5.30
	NO_x	1100.15	404.42	14.03
	PM	45.19	17.74	3.19
	Total	1,586.43	462.49	22.53

CHAPTER 8

HDVIP AND PSIP COST EFFECTIVENESS

As discussed in Section 7.1, the primary cost effectiveness of the HDVIP and PSIP cannot be estimated conventionally in terms of dollars per mass of pollution reduced. The primary focus of the HDVIP and PSIP is to reduce smoke emissions, a reduction which cannot be meaningfully addressed in terms of mass. As a result, primary program benefits were quantified in Section 7.1 in terms of the reduction in the number of excessively smoking heavy duty diesel vehicles operating in California.

As a secondary benefit, the HDVIP and PSIP also produce reductions in criteria pollutant emissions as a result of repairs performed to reduce excess smoke. These associated criteria pollutant impacts can be combined with program costs to derive a cost effectiveness estimate in units of dollars per pound of emission reduction. However, this cost effectiveness estimate only considers the secondary benefits of the HDVIP and PSIP.

As presented in Table 6-8, the net cost of the HDVIP and PSIP is estimated to be $19.4 million in 1999 and $17.3 million in 2010. The criteria pollutant emission reduction benefits of the programs are presented in Table 7-4 and total 23.84 tons per day in 1999 and 22.54 tons per day in 2010. Based on these estimates, the cost effectiveness of the secondary benefits of the HDVIP and PSIP is $1.12 per pound in 1999 and $1.05 per pound in 2010. Considering that emission control programs which primarily similar target criteria pollutant reductions typically cost between $2.50 and $5.00 per pound of emissions reduced, it is obvious that the HDVIP and PSIP are cost effective even if their primary smoke reduction benefits are not considered (i.e., when total program costs are assigned to secondary benefits only).

REFERENCES

1. **Air Resources Board**: Notice of Public Hearing, Staff Report, Technical Support Document, hearing transcript and Final Statement of Reasons for the initial adoption of the HDVIP regulations (11/8/90 hearing)

2. **Air Resources Board**: Notice of Public Hearing, Staff Report, Technical Support Document, hearing transcript and Final Statement of Reasons for the initial adoption of the HDVIP Administrative Hearings regulations (5/9/91 hearing)

3. **Air Resources Board**: Notice of Public Workshop (92-09), Notice of Public Hearing (92-49), Notice of Public Availability of Modified Text (93-09), hearing transcript, and Final Statement of Reasons for adoption of the PSIP regulations (December 10, 1992 hearing); transcript from December 9, 1994 hearing.

4. **Imperial County Superior Court, No. 72969**: Transcript from Valley Spreader lawsuit, (October 5 & 6, 1992).

5. **Society of Automotive Engineers**: Minutes and miscellaneous materials of SAE proceedings for the development of SAE J1667, including unconfirmed minutes, May 20, 1992 through June 4, 1996.

6. **Society of Automotive Engineers**: SAE J1667 Snap Acceleration Smoke Study Investigation of Characteristics of Various Filter Algorithms, May 14, 1995.

7. **SAE J1667/1 Task Group**: Correspondence from Ed Sienicki (Navistar Corporation), Chair, SAE J1667/1 Task Group, regarding analyses of correlation testing, May 10, 1996.

8. **Radian Corporation**: Heavy Duty Diesel Vehicle Inspection and Maintenance Study, (3 volumes), June 30, 1987.

9. **Air Resources Board, Technical Support Division**: EMFAC Modeling, (6 volumes) November 1996

10. **Manufacturers of Emission Controls Association**: Diesel Testing Program Report, March 1997.

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13. **dKC, Inc. for New Hampshire Department of Environmental Services**: A Study of Motor Vehicle Diesel Emissions and Control Strategies, January 21, 1997.

14. **Southwest Research Institute**: Statistical Review of Models to Correct for the Effects of Ambient Conditions on Heavy Duty In-Use Truck Smoke Opacity, May 1, 1995.

15. **Sierra Research, Inc.**: Implementation of a Roadside Emissions Inspection Program for Heavy -Duty Trucks, February 16, 1989.

16. **Sierra Research, Inc. and Energy and Environmental Analysis, Inc.**: Survey of Heavy Duty Diesel Engine Rebuilding and Reconditioning and Remanufacturing Practices, August 1997.

17. **Air Resources Board**: Correspondence to Heavy-duty Diesel Ad Hoc Advisory Committee Members; One-Hundred Vehicle Study Test Plan, December 13, 1996.

APPENDIX A

SAE J1667 Test Procedure

SAE The Engineering Society For Advancing Mobility Land Sea Air and Space INTERNATIONAL
400 Commonwealth Drive, Warrendale, PA 15096-0001

SURFACE VEHICLE RECOMMENDED PRACTICE

SAE J1667

Issued 1996-02

Submitted for recognition as an American National Standard

SNAP-ACCELERATION SMOKE TEST PROCEDURE FOR HEAVY-DUTY DIESEL POWERED VEHICLES

TABLE OF CONTENTS

Scope—This SAE Recommended Practice applies to vehicle exhaust smoke measurements made using the Snap-Acceleration test procedure. Because this is a non-moving vehicle test, this test can be conducted along the roadside, in a truck depot, a vehicle repair facility, or other test facilities. The test is intended to be used on heavy-duty trucks and buses powered by diesel engines. It is designed to be used in conjunction with smokemeters using the light extinction principle of smoke measurement.

This procedure describes how the snap-acceleration test is to be performed. It also gives specifications for the smokemeter and other test instrumentation and describes the algorithm for the measurement and quantification of the exhaust smoke produced during the test. Included are discussions of factors which influence snap-acceleration test results and methods to correct for these conditions. Unless otherwise noted, these correction methodologies are to be considered an integral part of the snap-acceleration test procedure.

1 **Purpose**—This document provides a procedure for assessing smoke emissions from in-use vehicles powered by heavy-duty diesel engines. Testing conducted in accordance with this procedure, in combination with reference smoke values, is intended to provide an indication of the state of maintenance and/or tampering of the engine and fuel system relative to the parameters which affect exhaust smoke. The procedure is expected to be of use to regulatory and enforcement authorities responsible for controlling smoke emissions from heavy-duty diesel-powered vehicles, and to heavy-duty vehicle maintenance and repair facilities. However, the procedure as written does not replicate the federal engine certification smoke cycle, and is intended to identify gross emitters. Regulatory agencies using this procedure must establish pass/fail criteria since SAE by-laws prohibit assignment of such criteria.

References

1 **Applicable Documents**—The following publications form a part of this specification to the extent specified herein. Unless otherwise specified, the latest issue of SAE publications shall apply.

1.1 SAE PUBLICATIONS—Available from SAE, 400 Commonwealth Drive, Warrendale, PA 15096-0001.

SAE J1349—Engine Power Test Code—Spark Ignition and Compression Ignition—Net Power Rating
SAE J1995—Engine Power Test Code—Spark Ignition and Compression Ignition—Gross Power Rating

2 **Related Publications**—The following publications are provided for information purposes only and are not a required part of this document.

2.1 SAE PUBLICATIONS—Available from SAE, 400 Commonwealth Drive, Warrendale, PA 15096-0001.

SAE J255a—Diesel Engine Smoke Measurement
SAE J1243—Diesel Emission Production Audit Test Procedure

2.2 ISO PUBLICATION—Available from ANSI, 11 West 42nd Street, New York, NY 10036-8002.

ISO CD 11614—Apparatus for the Measurement of the Opacity of the Light Absorption Coefficient of Exhaust Gas from Internal Combustion Engines

2.3 FEDERAL PUBLICATION—Available from The Superintendent of Documents, U.S. Government Printing Office, Washington, DC 20402.

Code of Federal Regulations (CFR), Title 40, Part 86, Subpart I—Emission Regulation for New Diesel Heavy-Duty Engines: Smoke Exhaust Test Procedure

2.2.4 OTHER

Procedures for Demonstrating Correlation Among Smokemeters

3. Definitions

3.1 Diesel Smoke—Particles, including aerosols, suspended in the exhaust stream of a diesel engine which absorb, reflect, or refract light.

3.2 Transmittance (T)—The fraction of light transmitted from a source which reaches a light detector.

3.3 Opacity (N)—The percentage of light transmitted from a source which is prevented from reaching a light detector. See Equation 1.

$$\text{Opacity \%} = 100 * (1 - \text{Transmittance}) \qquad \text{(Eq.1)}$$

3.4 Effective Optical Path Length (L) or (EOPL)—The length of the smoke obscured optical path between the smokemeter light source and detector. Note that portions of the total light source to detector path length which are not smoke obscured do not contribute to the effective optical path length.

3.5 Smoke Density (K)—(also known as "Light Extinction Coefficient" and "Light Absorption Coefficient") A fundamental means of quantifying the ability of a smoke plume or smoke containing gas sample to obscure light. By convention, smoke density is expressed on a per meter basis (m^{-1}). The smoke density is a function of the number of smoke particles per unit gas volume, the size distribution of the smoke particles, and the light absorption and scattering properties of the particles. In the absence of blue or white smoke, the size distribution and the light absorption/scattering properties are similar for all diesel exhaust gas samples and the smoke density is primarily a function of the smoke particle density.

3.6 Beer-Lambert Law—A mathematical equation describing the physical relationships between the smoke density (K) and the smoke parameters of transmittance (T), and effective optical path length (L). Because smoke density (K) cannot be measured directly, the Beer-Lambert equation is used to calculate (K), when opacity (N) and EOPL (L) are known.

3.7 Smoke Opacimeter—A type of smokemeter designed to measure the opacity of a plume or sample of smoke by means of a light extinction principle.

3.8 Full-Flow End-of-Line Smokemeter—A smokemeter which measures the opacity of the full exhaust plume as it exits the tailpipe. The light source and detector for this type of smokemeter are located on opposite sides of the smoke plume and in close proximity to the open end of the tailpipe. When applying this type of smokemeter, the effective optical path length is a function of the tailpipe design.

3.9 Sampling Type Smokemeter (Also called Partial Flow Smokemeter)—A smokemeter which continually samples a representative portion of the total exhaust flow and directs it to a measurement cell. With this type of smokemeter, the effective optical path length is a function of the smokemeter design.

3.10 Smokemeter Measurement Zone—The effective length between the smokemeter light source and light detector through which exhaust gases pass and interact with the smokemeter light beam.

3.11 Smokemeter Response Time—See 6.3 and Appendix A.

.12 Smokemeter Linearity—A measure of the maximum absolute deviation of values measured by the smokemeter from the reference values.

. *Special Notes and Conventions*

.1 The term smokemeter is a broad term which applies to all smoke-measuring devices regardless of the smoke-sensing technique employed. Throughout this document, the term smokemeter will refer only to opacimeter type smokemeters.

.2 To fully describe the light obscuration properties of a smoke sample (i.e., smoke density), opacity (N) must always be associated with an EOPL. Whenever specific smoke opacity values are referenced in this document, the associated effective optical path length is understood to be 0.127 m (5 in).

. *Snap-Acceleration Test*—The complete Snap-Acceleration process consists of five phases. These phases are:

a. Vehicle Preparation and Safety Check
b. Test Preparation and Equipment Set-up
c. Driver Familiarization and Vehicle Preconditioning
d. Execution of the Snap-Acceleration Test
e. Calculation and Reporting of Final Results

.1 **Vehicle Preparation and Safety Check**—Prior to conducting the snap-acceleration test, the following items must be completed:

a. If the vehicle is equipped with a manual transmission, the transmission must be placed in neutral and the clutch must be released.

   If the vehicle is equipped with an automatic transmission, the transmission must be placed in the park position, if available, or otherwise in the neutral position.

b. The vehicle wheels must be chocked or the vehicle must be otherwise restrained to prevent the vehicle from moving during the testing.

c. Vehicle air conditioning should be turned off.

d. If the engine is equipped with an engine brake, it must be deactivated during the snap-acceleration testing.

e. All devices installed on the engine or vehicle which alter the normal acceleration characteristics of the engine and have the effect of temporarily lowering snap-acceleration test results, or preventing the test from being successfully completed, shall be deactivated prior to testing.

f. Verify the speed-limiting capability of the engine governor using the following procedure:

   With the engine at low idle, slowly depress the engine throttle and allow the engine speed to gradually increase toward its maximum governed high idle speed. As the engine speed increases, carefully note any visual or audible indications that the engine or vehicle may be of questionable soundness. If there are no indications of problems, allow the engine speed to increase to the point that it is possible to verify that the speed-limiting capability of the governor is functioning. Should there be any indication that the speed-limiting capability of the governor is not functioning, or that potential engine damage, or unsafe conditions for personnel or equipment may occur, the throttle should immediately be released and the snap-acceleration testing of the vehicle shall be aborted.

g. The vehicle should be inspected for exhaust leaks. Severe leaks in the system may cause the introduction of air into the exhaust stream which may cause erroneously low test results.

h. Users must be cautioned regarding the observance of blue or white smoke in the exhaust. Blue smoke can be an indicator of unburned hydrocarbons (possible oil burning or malfunctioning nozzle), and white smoke can be an indicator of water vapor (possible internal coolant leaking conditions).

5.2 Test Preparation and Equipment Set-up

5.2.1 Ambient Air Test Conditions—Ambient air conditions can affect snap-acceleration smoke test results. To ensure reliable results, the correction factors in Appendix B should be applied to snap-acceleration testing results to account for normal changes in ambient conditions. However, these correction factors must be applied under the following conditions.

a. Altitude—Greater than 457 m (1500 ft) above sea level.

b. Air Temperature—Above or below the range of 2 to 30 °C (36 to 86 °F).

c. Wind—Excessively windy conditions should be avoided. Winds are excessive if they disturb the size, shape, or location of the vehicle exhaust plume in the region where exhaust samples are drawn or where the smoke plume is measured. The effect of wind may be eliminated or reduced by locating the vehicle in a wind-sheltered area or by using measuring equipment designs which preclude wind effects on the smoke in the measuring or sampling zones.

d. Dry Air Density—If the correction factors referenced in Appendix B are used, the useful range of dry air densities are: 0.908 to 1.235 kg/m^3 (0.0567 to 0.0771 lbm/ft^3). This range of dry air densities is based on air densities experienced during ambient conditions testing.

e. Humidity—No visible humidity (including fog, rain, and snow) in the region where exhaust samples are drawn or the smoke plume is measured. Some equipment designs preclude the effects of these conditions.

5.2.2 Smokemeter Installation—The smokemeter and other test equipment used for snap-acceleration tests shall meet the specifications of 6.1 through 6.5. The general installation procedures specified by the smokemeter manufacturer shall be followed when preparing to test a vehicle.

In addition, these special installation procedures shall be followed:

a. If the test results are to be reported in units of smoke opacity, the rated power of the engine should be determined. The rated power is needed to define the standard effective optical path length used to correct the as-measured smoke opacity to standard conditions as described in Appendix C. The rated power should be available from the tune-up label fixed to the engine or from literature supplied to the owner by the engine manufacturer. In some cases, particularly under roadside test conditions, it may not be possible to readily determine the rated engine power. In these cases, it is recommended that the OD of the vehicle tailpipe section be determined and used as the standard effective optical path length for the purposes of the Beer-Lambert corrections described in Appendix C. If the rated engine power becomes available after the test is run, the test result should be recorrected as necessary using Equation C3 and the appropriate standard effective optical path length from Table C1.

Sampling in or immediately downstream of bends such as curved stack outlets in the exhaust pipe may cause some variability between individual Snap-Acceleration cycle readings.

b. For Full Flow End-of-Line Type Smokemeters—The axis of the smokemeter light beam shall be perpendicular to the axis of the exhaust flow. The centerline of the light beam axis should be located as close as possible, but in no case further than 7 cm (2.76 in) from the exhaust outlet. Appendix D provides additional guidance for smokemeter replacement.

Determine the effective optical path length used to make the smoke measurements. For straight tailpipes of circular cross section, the effective optical path length is equal to the tailpipe ID, and for tubing construction can be reasonably approximated by the tailpipe OD. Appendix D provides guidance for determining the as-measured effective optical path length when irregular tailpipe configurations are encountered. The as-measured effective optical path length is required to convert measured smoke values to standard corrected smoke values using the procedures described in Appendix C.

c. For Sampling Type Smokemeters—The probe of the sampling type smokemeter shall be inserted into the exhaust tailpipe with the open end facing upstream and into the exhaust flow.

The clearance between the inside edge of the open end of the sample probe and the tailpipe wall must be at least 5 mm (0.197 in).

Only the probe and sampling pipe, or tubing, specified by the manufacturer of the smokemeter shall be used for the smoke sampling. Manufacturer's recommendations regarding the length of the sample line shall be adhered to.

d. Multiple Exhaust Outlets—When testing vehicles equipped with multiple exhaust outlets, such as dual exhaust systems originating from a single manifold or single pipe, it is normally not necessary to measure the smoke from each exhaust outlet. The following approach is suggested.

If there is no discernible difference in the exhaust smoke exiting from each multiple exhaust outlet, the smoke should be measured from the exhaust outlet that provides the most convenient meter installation. A visual observation of one or more preliminary snap-acceleration test cycles should be sufficient to make this determination.

Should there be a discernible difference in the smoke exiting from the multiple exhaust outlets, install the smokemeter and conduct the snap-acceleration test on the exhaust outlet that visually appears to have the highest smoke level.

.2.3 A tachometer to measure the engine speed may be installed and calibrated per the manufacturer's recommendations. A tachometer provides useful data regarding idle RPM, maximum engine RPM, the time necessary for the operator to accelerate the engine from idle to maximum RPM, and the time the engine speed was held at maximum RPM. This information helps to ensure repeatability between test cycles.

.3 Driver Familiarization and Vehicle Preconditioning

.3.1 Prior to the preconditioning test, the vehicle should be operated under load for at least 15 min to ensure that the engine is warmed-up. Alternatively, vehicle water and oil temperature gages may be checked to verify that the engine is within its normal operating temperature range.

5.3.2 SNAP-ACCELERATION CYCLE—The vehicle operator shall be instructed on the proper execution of the snap-acceleration test sequence. It is of critical importance that the vehicle operator fully understand the proper movement of the vehicle throttle during the testing.

With the vehicle conditioned as in 5.1 and with the engine warmed-up and at low idle speed:

a. The operator shall move the throttle to the fully open position as rapidly as possible.

b. The operator shall hold the throttle in the fully open position until the time the engine reaches its maximum governed speed, plus an additional 1 to 4 s.

c. Upon completion of the 1 to 4 s with the engine at its maximum governed speed, the operator shall release the throttle and allow the engine to return to the low idle speed.

d. Once the engine reaches its low idle speed, the operator shall allow the engine to remain at idle for a minimum of 5 s, but no longer than 45 s, before initiating the next snap-acceleration test cycle.

   The time period at low idle allows the engine's turbocharger (if so equipped) to decelerate to its normal speed at engine idle. This helps to reduce the smoke variability between snap-acceleration cycles.

e. Steps (a) through (d) shall be repeated as necessary to complete the preliminary snap-acceleration cycles and the snap-acceleration test cycles described in 5.3.3 and 5.4.2.

5.3.3 PRELIMINARY SNAP-ACCELERATION TEST CYCLES—The vehicle shall receive at least three preliminary snap-acceleration test cycles using the sequence described in 5.3.2. The preliminary cycles allow the vehicle operator to become familiar with the proper throttle movement, and also remove any loose soot which may have accumulated in the vehicle exhaust system during prior operation.

If smoke measurements are made during the preliminary cycles, the preliminary cycles can also provide the opportunity to check for proper operation of the smoke measurement system, and to check if the test validation criteria of 5.4.4 can be met. In this case, the data-processing unit and the smokemeter zero and full scale should first be set according to 5.4.1 and 5.4.2.

5.4 Execution of the Snap-Acceleration Test

5.4.1 DATA PROCESSING UNIT SET-UP—Before snap-acceleration testing can proceed, the smokemeter data processing unit must be properly set up. The operating instructions supplied by the processing unit manufacturer should be consulted for specific set-up procedures; however, the following functional steps must be accomplished.

a. If a multi-mode test system is used, the appropriate mode for snap-acceleration testing must be selected.

b. The desired smoke output units (opacity or smoke density) must be selected.

c. If the Beer-Lambert corrections as described in Appendix C are to be performed within the data-processing unit, values must be supplied for the standard and as-measured effective optical path lengths if opacity output is desired and for the as-measured effective optical path lengths if smoke density output is desired. Appendices C and D provide guidance in determining these input values.

d. If a red LED smokemeter light source is used and light source wavelength corrections are to be performed within the data-processing unit, the appropriate selections must be made to trigger these calculations (see Appendix C).

e. If the ambient condition corrections described in Appendix B are to be performed automatically by the data-processing unit, the appropriate ambient parameters must be input.

f. Any additional test identification information consistent with the needs of the test program and capabilities of the data-processing unit should be supplied at this time. Normally this would include the test date, test operator, vehicle identification, and other such information.

5.4.2 SMOKEMETER ZERO AND FULL SCALE—Prior to conducting smoke measurements, the zero and full scale readings of the smokemeter shall be verified. (Some meter systems may automatically perform the zero and full scale checks. For other meters, this sequence will need to be done manually.) Should optional recording devices be part of the test set-up, this equipment should also be checked for proper operation and calibration.

a. Smokemeter Warm-up—Prior to any zero and/or full-scale checks or adjustments, the smokemeter shall be warmed up and stabilized according to the manufacturer's recommendations. If the smokemeter is equipped with a purge air system to prevent sooting of the meter optics, this system should also be activated and adjusted according to the manufacturer's recommendations.

b. Smokemeter Zero—With the smokemeter in the Opacity readout mode, and with no blockage of the smokemeter light beam, adjust the readout to display 0.0% ± 1.0% opacity.

c. Smokemeter Full Scale—With the smokemeter in the Opacity readout mode, and all light prevented from reaching the detector, adjust the readout of the smokemeter to display 100.0% ± 1.0% opacity.

NOTE—For Smokemeter readouts in units of Smoke Density (K).

Smoke density (K) is a calculation based upon opacity and EOPL. The opacity scale offers two truly definable calibration points, namely 0% opacity and 100% opacity. The upper end of the smoke density scale is infinite, which makes this point on the K scale undefined. Because of this, the preferred method to set the zero and full scale of the meter when measuring in either smoke density (K) or opacity (N) units is to set the meter to the opacity readout mode and make the zero and full-scale adjustments as described in 5.4.2 (a) to (c). The smoke density would then be correctly calculated based upon the measured opacity and, of course, the EOPL, when the meter is returned to the smoke density readout mode for testing.

However, if this technique is not possible, it is acceptable to set the zero and span of the smokemeter in units of smoke density (K) with the use of a neutral density filter of known value. Should this be the case, the smokemeter zero and span shall be set as follows:

d. Smokemeter Zero—With the smokemeter in the Smoke Density (K) readout mode, and with no blockage of the smokemeter light beam, adjust the readout to display 0.00 m^{-1} ± 0.10 m^{-1}.

e. Smokemeter Span (If required by the smokemeter manufacturer)—With the smokemeter in the Smoke Density (K) readout mode, place a neutral density filter of known value between the light emitter and detector. The neutral density filter shall meet the accuracy requirements of 6.2.10 and have a known nominal value in the range of 1.5 to 5.5 m^{-1}. Adjust the smokemeter readout to display the filter nominal value, ±0.10 m^{-1}.

NOTE—Neutral density calibration filters are precision devices and can easily be damaged during use. Handling should be minimized and, when required, should be done with care to avoid scratching or dirtying of the filter.

5.4.3 SNAP-ACCELERATION TEST CYCLES—Within 2 min of the execution of the preliminary snap-acceleration cycles, conduct three snap-acceleration test cycles, actuating the vehicle throttle in the manner and sequence described in 5.3.2 (a to e).

Determine the corrected maximum 0.5 s average smoke values for each of the three snap-acceleration cycles using the smoke data processing algorithms described in Appendices A and C.

At the conclusion of the test sequence, and where needed as per manufacturer's recommendation, determine the degree of smokemeter zero shift by eliminating all exhaust from between the smokemeter light source and detector and noting the smokemeter display.

5.4.4 TEST VALIDATION CRITERIA—The test results from 5.4.3 shall be considered valid only after the following criteria have been met.

a The post-test smokemeter zero shift values shall not exceed:

(1) ±2.0% opacity—For smoke measurements made in opacity.

(2) ±0.15 m^{-1}—For smoke measurements made in smoke density (K).

b. The arithmetical difference between the highest and lowest corrected maximum 0.5 s average smoke values from the three test cycles shall not exceed:

(1) 5.0% opacity—For smoke measurements made in opacity.

(2) 0.50 m^{-1}—For smoke measurements made in smoke density (K).

5.4.5 INVALID TESTS—Should the smoke test data from 5.4.3 not meet the test validation criteria of 5.4.4, the following items should be checked as possible causes for the invalid test results:

a. If the engine did not meet the operating temperature requirements, run the engine/vehicle under load for at least 15 min or until the vehicle oil and water temperature gages indicate that normal engine operating temperatures have been achieved. Return to 5.2.2 (Smokemeter Installation) and repeat the test sequence.

b. If improper or inconsistent application of the vehicle throttle is suspected, re-instruct the vehicle operator as to the proper execution of the snap-acceleration test, especially the movement of the vehicle throttle, as detailed in 5.3.2. Continue on with the procedure at this point and repeat the preliminary test cycles and the snap-acceleration test sequence while observing the vehicle operator.

c. Check the smokemeter, its installation on the tailpipe, and any support instrumentation for possible malfunctions. Correct as necessary and then return to 5.3.3 (Preliminary Snap-Acceleration Test Cycles), and repeat the test sequence.

d. If the post-test smokemeter zero check was exceeded due to positive zero drift, the probable cause is soot accumulation on the smokemeter optics. It is recommended that the snap-acceleration test sequence be repeated and while doing so, the smokemeter zero may be readjusted during the low idle period between each of the snap-acceleration test cycles. If the measured low idle smoke level of the vehicle is less than 2.0% opacity or 0.20 m^{-1} smoke density, it is permissible to re-zero the meter while it remains exposed to the vehicle exhaust. If the idle smoke level exceeds these limits, it is necessary to discontinue exposure to exhaust before rezeroing the meter.

It is not necessary to complete an invalid test before employing the rezeroing technique discussed previously. If comparison of the low idle smoke readings shows an increasing trend from one test cycle to the next, sooting of meter optics can be suspected and the rezeroing technique can immediately be used.

If it is not possible to rezero the meter, the meter optics should be cleaned per the smokemeter manufacturer's recommended procedures and the test sequence should be repeated beginning at 5.3.3 (preliminary snap-acceleration test cycles). If zero drift and rezeroing difficulties persist, it is recommended that the meter purge air system (if so equipped) be checked for proper operation.

e. If the procedure has been repeated in accordance with the requirements stated in 5.4.5 (a to d), and the test results still cannot be obtained that conform with the test validation criteria, then it is likely that the engine is in need of service.

5.5 **Calculation and Reporting of Final Test Result**—If the validation criteria of 5.4.4 are met, the data shall be deemed valid and the test complete. The average of the corrected maximum 0.5 s average smoke values from the three snap-acceleration test cycles shall be computed and reported as the final test result. (See Appendix A.)

6. ***Test Instrumentation Specifications***—This section provides specifications for the required and optional test equipment used in the snap-acceleration test.

6.1 **General Requirements for the Smoke Measurement Equipment**—The snap-acceleration smoke test requires the use of a smoke measurement and data-processing system which includes three functional units. These units may be integrated into a single component or provided as a system of interconnected components. The three functional units are:

a. A full-flow end-of-line or a sampling type smokemeter meeting the specifications of 6.2 through 6.4. .

b. A data-processing unit capable of performing the functions described in Appendices A and C.

c. A printer and/or electronic storage medium to record and output the individual corrected maximum 0.5 s average smoke values from each snap-acceleration test cycle, and the final average snap-acceleration test result.

6.2 **Specific Requirements for the Smoke Measurement Equipment**

6.2.1 LINEARITY—±2% opacity or ±0.30 m^{-1} density.

6.2.2 ZERO DRIFT RATE—Not to exceed ±1% opacity/hour.

6.3 Instrument Response Time Requirements

6.3.1 OVERALL INSTRUMENT RESPONSE TIME REQUIREMENT—The overall instrument response time (t) shall be: 0.500 s ± 0.015 s. It is defined as the difference between the times when the output of the smokemeter reaches 10% and 90% of full scale when the opacity of the gas being measured is changed in less than 0.01 s. It shall include all the physical, electrical, and filter response times. Mathematically, it is represented by Equation 2. (See Appendix A for a more detailed methodology and an example calculation.)

$$t = SQRT\ (t_p^2 + t_e^2 + t_F^2) \quad \text{(Eq.2)}$$

where:

t_p = The physical response time
t_e = The electrical response time
t_F = The filter response time

6.3.2 PHYSICAL RESPONSE TIME (t_p)—This is the difference between the times when the output of a rapid response receiver (with a response time of not more than 0.01 s) reaches 10% and 90% of the full deviation when the opacity of the gas being measured is changed in less than 0.1 s.

The physical response time is defined for the smokemeter only and excludes the probe and sample line. However, on some in-use smokemeter systems, the probe and sample line may significantly affect the overall response time of the system. If necessary, this shall be taken into account for any particular smokemeter system.

For full-flow type smokemeters, the response time is a function of the velocity of flow in the vehicle exhaust pipe and the path length across the detector (detector diameter). It can be assumed equal to a negligible 0.01 s. For sampling type smokemeters where the measuring zone is a straight section of pipe of uniform diameter, the physical response can be estimated by Equation 3:

$$t_p = 0.8 * V/Q \quad \text{(Eq.3)}$$

where:

Q = The rate of flow of gas through the measuring zone
V = The volume of the measuring zone

For such instruments, the speed of the gas through the measuring zone shall not differ by more than 50% from the average speed over 90% of the length of the measuring zone.

For all smokemeters, if the physical response calculates greater than 0.2 s, then the response time shall be measured.

6.3.3 ELECTRICAL RESPONSE TIME (t_e)—It is defined as the time needed for the recorder output to go from 10% of the maximum scale to 90% of the maximum scale value when a fully opaque screen is placed in front of the photo cell in less than 0.01 s, or the LED is turned off. This is to include all of the effects of recorder output response time.

.3.4 FILTER RESPONSE TIME (t_F)—Filtering of the smoke signal will be necessary on most smokemeters to achieve an overall response time of 0.500 s ± 0.015 s. Most smokemeters have a very fast electrical response time, but physical response times will vary from one device to the next depending on design and gas flow.

Appendix A specifies the recommended second-order digital filtering algorithm to be used.

.3.5 DETERMINATION OF THE PEAK SMOKE VALUE—An algorithm in Appendix A shall be used to determine the reported peak exhaust smoke levels.

.4 Smokemeter Light Source and Detector

.4.1 LIGHT SOURCE—The light source shall be an incandescent lamp with a color temperature in the range of 2800 to 3250 °K, or a green light emitting diode (LED) with a spectral peak between 550 and 570 nm.

Alternatively, a red LED may be used provided that the appropriate light wavelength correction is made as described in Appendix C.

.4.2 LIGHT DETECTOR—The light detector shall be a photocell or a photodiode (with a filter, if necessary). In the case of an incandescent light source, the detector shall have a peak spectral response in the range of 550 to 570 nm, and shall have a gradual reduction in response to values of less than 4% of the peak response value below 430 nm and above 680 nm.

.4.3 The rays of the light beam shall be parallel within a tolerance of 3 degrees of the optical axis. The detector shall be designed such that it is not affected by direct or indirect light rays with an angle of incidence greater than 3 degrees to the optical axis.

.4.4 Any method such as purge air which is used to protect the light source and detector from direct contact with exhaust soot shall be designed to minimize any unknown effect on the effective optical path length of the measured smoke (see C.5.1). For full-flow end-of-line smokemeters, the protection feature must not cause the smoke plume to be distorted by more than 0.5 cm. For sampling type smokemeters, the meter manufacturer must account for any effect of the protection feature in specifying the effective optical path length of the meter.

4.5 The sampling and digitization rate of the data processing units shall be at least 20 Hz (i.e., at least 10 data samples per 0.5 s interval). Additionally, the product of the data sampling time increment (seconds) and one half the data sample rate (Hz) rounded to the next higher integer value must be within the range of 0.500 to 0.510 s.

5 Specifications for Auxiliary Test Equipment

5.1 NEUTRAL DENSITY FILTERS—Any neutral density filter used in conjunction with smokemeter calibration, linearity measurements, or setting span shall have its value known to within 0.5% opacity or 0.04 m^{-1}. The filter's named value must be checked for accuracy at least yearly using a reference traceable to a national standard.

5.2 If altitude correction (i.e., the altitude is greater than 457 m (1500 ft)) then:

a. Equipment used to measure barometric pressure must be accurate within ±0.30 kPa (±0.089 in-Hg)

b. Ambient dry bulb temperature must be accurate within ±2 °C (±3.6 °F)

6.5.3 Measurement of the following parameters is optional; however, if measured, the specified accuracy requirements should be met:

a. Ambient Dry Bulb Temperature—±2 °C (±3.6 °F)
b. Dew Point Temperature—±2 °C (±3.6 °F)
c. Engine Speed—±100 rpm

6.5.4 OPTIONAL RECORDING DEVICES—A supplemental chart recorder or other collection media may be used provided that the device(s) does not affect the smoke measurement.

7. ***Smokemeter Maintenance and Calibration***—The smokemeter should be maintained and serviced per the manufacturer's recommendations. In addition to the zero and span adjustments to be made prior to each snap-acceleration test (5.4.2), the linearity of the meter response should be periodically checked as per manufacturer's recommendations in the range of measurement interest using neutral density filters meeting the requirements of 6.5.1. Non-linearities in excess of 2% opacity or 0.30 m^{-1} smoke density should be corrected prior to resuming testing with the meter.

PREPARED BY THE SAE HEAVY-DUTY IN-USE EMISSION STANDARDS COMMITTEE

APPENDIX A
SECOND-ORDER FILTER ALGORITHM USED TO CALCULATE A MAXIMUM 0.500 s AVERAGE SMOKE VALUE

A.1 *Introduction*—This appendix explains how to create and use the recommended Bessel low-pass digital filter algorithm in a smokemeter to filter out the high-frequency smoke readings which are produced during a snap-acceleration test. This appendix in particular describes the methodology used to design a low-pass second-order Bessel filter with a response time as needed for a particular smokemeter application. This appendix also describes the procedure for determining the final snap-acceleration test. Two example calculations detailing the selection of Bessel filter coefficients and their use are also provided in this appendix to illustrate the concepts more clearly.

The digital Bessel filter described in this appendix is a second-order (2-pole) low-pass digital filter algorithm. It is the recommended filter to be used for designing smokemeters with 0.500 s overall response times as required in 6.3. The Bessel filter type was chosen because it allows passage of all signals which do not change very much with time, but effectively blocks all signals with higher-frequency components. Its linear-phase characteristics also enable it to approximate a constant time delay over a limited frequency range. Transient waveforms can also be passed with minimal distortion when it is used as a running average type filter. A digital approach was chosen due to the relative ease of implementing a software algorithm in most smokemeters. However, analog Bessel filters using the appropriate electronic circuits may also be used.

A.2 *Definitions*

B = Bessel parameter constant. It equals [Sqrt(5)−1]/2
f_c = Bessel cutoff frequency used to control the filtered response
t_e = Electrical response time of the smokemeter (seconds)
t_F = Filter response time (seconds)
t_{Fd} = Desired filter response time (seconds)
t_p = Physical response time of the smokemeter (seconds)
t_{10} = The test time when the output response to an input step response is equal to 10% of the step input
t_{90} = The test time when the output response to an input step response is equal to 90% of the step input
Δt = Time between two stored opacity values (i.e., sampling period (seconds))
X_i = Bessel filter input at sample number (i)
X_{i-1} = Bessel filter input at sample number (i−1)
X_{i-2} = Bessel filter input at sample number (i−2)
Y_i = Bessel filter output at sample number (i)
Y_{i-1} = Bessel filter output at sample number (i−1)
Y_{i-2} = Bessel filter output at sample number (i−2)

A.3 Designing a Bessel Low-Pass Filter—Designing the 0.500 s Bessel low-pass digital filter is a multistep process which may involve several iterative calculations to determine coefficients. This section provides a method for determining the desired amount of filtering for smokemeters with different electrical and physical response times, or different sample rates. Bessel filters can be designed to accommodate filter designs having response times ranging from 0.010 to 0.500 s, and digitization rates of 50 Hz and higher.

It is recommended that all Bessel filter calculations be performed in opacity units for the sake of consistency between smokemeters. If smokemeter output in units of density need to be reported, the Beer-Lambert law may be used to convert the final opacity results to density results, and perform any necessary stack size correction. This conversion should be done only after all Bessel filter equations have been performed due to the non-linearity of the Beer-Lambert law.

A.3.1 Calculating the Desired Filter Response Time (t_{Fd})—Prior to designing a digital Bessel filter, it is necessary to determine the physical response time (t_p) and the electrical response time (t_e) for the relevant smokemeter. These parameters are necessary in order to determine how much electronic filtering is necessary to achieve an overall 0.500 s response time. For some partial flow smokemeters this may require experimental data. For other smokemeters the procedures and equations in 6.3 may be used.

Once the values of t_p and t_e are known, the desired filter response time (t_{Fd}) can be determined by using Equation A1.

$$t_{Fd} = \text{SQRT}\,[0.500^2 - (t_p^2 + t_e^2)] \qquad \text{(Eq.A1)}$$

A.3.2 Estimating Bessel Filter Cutoff Frequency (f_c)—The Bessel filter response time (t_F) is defined as the time in which the output signal (Y_i) reaches 10% (Y_{10}) and 90% (Y_{90}) of a full-scale input step (X_i) which occurs in less than 0.01 s. The difference in time between the 90% response (t_{90}) and the 10% response time (t_{10}) defines the response time (t_F). Thus,

$$(t_F) = (t_{90}) - (t_{10}) \qquad \text{(Eq.A2)}$$

For the filter to operate properly, the filter response time (t_F) should be within 1% of the desired response time (t_{Fd}), that is, $[(t_F) - (t_{Fd})] < [0.01 * (t_{Fd})]$.

To create a filter where t_F approximates t_{Fd}, the appropriate cutoff frequency (f_c) must be determined. This is an iterative process of choosing successively better values of (f_c) until $[(t_F) - (t_{Fd})] < [0.01 * (t_{Fd})]$.

The first step in the process is to calculate a first guess value for f_c using Equation A3.

$$f_c = \pi/(10 * t_{Fd}) \qquad \text{(Eq.A3)}$$

The values of B, Ω, C, and K are then calculated using Equation A4 through A7.

$$B = 0.618034 \qquad \text{(Eq.A4)}$$

$$\Omega = 1/[\tan(\pi * \Delta t * f_c)] \qquad \text{(Eq.A5)}$$

$$C = 1/[1 + \Omega^*sqrt(3^*B) + B^*\Omega^2] \quad (Eq.A6)$$

$$K = 2 * C * [B^*\Omega^2 - 1] - 1 \quad (Eq.A7)$$

Δt = Time between two stored opacity values (i.e., sampling period (seconds)).

The values of K and C are then used in Equation A8 to calculate the Bessel filter response to the given step input. Because of the recursive nature of Equation A8, the values of X and Y listed as follows are used to begin the process.

$$Y_i = Y_{i-1} + C^*[X_i + 2^*X_{i-1} + X_{i-2} - 4^*Y_{i-2}] + K^*(Y_{i-1} - Y_{i-2}) \quad (Eq.A8)$$

where:

$X_i = 100$
$X_{i-1} = 0$
$X_{i-2} = 0$
$Y_{i-1} = 0$
$Y_{i-2} = 0$

As shown in the example (A.7.1), calculate Y_i for successive values of $X_i = 100$ until the value of Y_i has exceeded 90% of the step input (X_i). The difference in time between the 90% response (t_{90}) and the 10% response (t_{10}) defines the response time (t_F) for that value of (f_c). Since the data are digital, linear interpolation may be needed to precisely calculate t_{10} and t_{90}.

If the response time is not close enough to the desired response time {that is, if $[(t_F)-(t_{Fd})] > [0.01^*(t_{Fd})]$}, then the iterative process must be repeated with a new value of (f_c). The variables (t_F) and (f_c) are approximately proportional to each other, so the new (f_c) should be selected based on the difference between (t_F) and (t_{Fd}) as shown in the example calculations (A.5.1).

A.4 Using the Bessel Filter Algorithm—The proper cutoff frequency (f_c) is the one that produces the desired filter response time (t_{Fd}). Once this frequency has been determined through the iterative process, the proper Bessel filter algorithm coefficients for Equation A4 through A7 are specified. Equation A8 and the coefficients can then be programmed into the smokemeter to produce the desired filter.

The Bessel filter equation (Equation A8) is recursive in nature. Thus, it needs some initial input values of X_{i-1} and X_{i-2} and initial output values Y_{i-1} and Y_{i-2} to get the algorithm started. These may be assumed to be 0% opacity. A detailed example calculation is shown in A.7.3.

A.5 Determining the Maximum 0.500 s Averaged Smoke Value—The maximum smoke value for a snap-acceleration test cycle (Y_{max}) is then selected from among the individual Y_i values computed using Equation A8 (after suitable Beer-Lambert and light source wavelength corrections are applied). This is the final test result for the test cycle and is used in combination with the results from the other snap-acceleration cycles in the test to determine a final snap-acceleration test result.

In equation form:

$$Y_{max} = \text{Maximum}(Y_i) \quad \text{(Eq.A9)}$$

A.6 Determination of the Final Test Result—If the test validation criteria of 5.4.4 have been met, the final snap-acceleration test result shall be computed by taking the simple average of the three corrected maximum 0.500 s averaged smoke values obtained from the three snap-acceleration test cycles.

$$A = (Y_{max,1} + Y_{max,2} + Y_{max,3})/3 \quad \text{(Eq.A10)}$$

A.7 Example of Incorporating a Bessel Filter Into a Smokemeter Design—This example illustrates how a full flow meter with a fast physical and electrical response time can implement the Bessel filter algorithm. The sample smokemeter has the following characteristics:

a. Physical Response Time = 0.020 s
b. Electrical Response Time = 0.010 s
c. Sampling Rate = 100 Hz
d. Sampling Period = 0.01 s

A.7.1 First Iteration to Estimate Bessel Function Cutoff Frequency (f_c)—This section displays the initial calculations which are performed to estimate the correct value of the cutoff frequency (f_c).

The results from Equation A1 indicate that the desired filter response (t_{Fd}) is 0.4995 (for simplicity, a value of 0.50 will be used in the sample calculations). This may be typical of a full flow meter with a very fast electrical and physical response time. It suggests that most of the desired 0.500 s filtering will be performed by the digital filter rather than the instrument.

$$t_{Fd} = 0.4995 = \text{SQRT}[0.500^2 - (0.020^2 + 0.010^2)] \quad \text{(Eq.A11)}$$

By inserting the correct values of Δt and t_F into Equations A2 through A7, the Bessel function coefficients are determined. These are shown in Table A1.

TABLE A1—INITIAL BESSEL COEFFICIENTS

Equation A1	t_F	0.500
Equation A2	f_c	0.6283
Equation A4	B	0.618
Equation A5	Ω	50.6555063
Equation A6	C	0.00060396
Equation A7	K	0.91427037
	Δt	0.01

The Bessel coefficients can now be inserted into Equation A8 along with the step input function (i.e., an input of 0% opacity to 100% opacity in 0.01 s) to illustrate the effect of the Bessel filter on the step response as a function of time. The input step function is shown as X_i in Table A2. To simulate the step response, input X_1 = 100. This will create the sudden jump from 0 to 100%.

The Bessel filtered output is shown as Y_i in Table A2. The two output points which are of interest are the 10% response point and the 90% response point. These are the values where Y_i first exceeds 10% and 90%. Since the output Y_i is digital, the exact 10% and 90% points must be interpolated from Table A2. The four points which bound the 10% and 90% points are indicated by an "X" in the index column of Table A2. These are index numbers 9, 10, and 64, 65.

For this specific case, the following interpolation formulas are used to calculate the values of $t_{10\%}$ and $t_{90\%}$.

$$t_{10\%} = 0.01 * [9 + (10 - 8.647)/(10.260 - 8.647)] = 0.0984 \text{ s} \qquad \text{(Eq.A12)}$$

$$t_{90\%} = 0.01 * [64 + (90 - 89.834)/(90.427 - 89.834)] = 0.6428 \text{ s} \qquad \text{(Eq.A13)}$$

Now calculate the difference between $t_{90\%}$ and $t_{10\%}$ and see if it is close enough to t_F (close enough means within 1% or in this case 0.005).

$$0.6428 - 0.0984 = 0.5444 \text{ s} \qquad \text{(Eq.A14)}$$

The calculation shows that the response time of the filter is 0.5444 s using a value of f_c of 0.6283. The difference between this value and the desired value of 0.50 is 0.0444 which is about 10% greater than desired. Thus, another attempt to reach the desired response time will have to be made. Since 0.5444 is about 10% too high, use a cutoff frequency (f_c) which is 10% larger for the second iteration.

7.2 Second Iteration to Estimate Bessel Function Cutoff Frequency (f_c)—For the second iteration, a value of 0.690 is chosen for the value of f_c. This is approximately 10% higher than the value previously used. When this value is used, the Bessel function coefficients in Table A3 are obtained.

The filter responses Y_i were also recalculated for the step input X_i. The entire table of inputs (X_i) and responses (Y_i) (analogous to Table A2) is not shown. However, the values of t_{10} and t_{90} and the difference between were calculated and are shown in Table A4. In this case, the difference between the filter response time and the desired filter response time of 0.50 s is 0.0049. This is less than the 1% difference criteria (0.005 s). Thus, the value of 0.692 for the frequency cutoff (f_c) is the correct one for this smokemeter application.

7.3 Sample Calculation of the Bessel Filter Opacity Response—Once the appropriate value for the cutoff frequency (f_c) has been determined, then Equations A4 through A8 are used to calculate the Bessel filtered opacity values (Y_i) for any given input opacity values (X_i). The maximum filtered response is then selected and reported as the smoke reading for that particular snap-acceleration cycle.

TABLE A2—INITIAL SIMULATION OF THE BESSEL FILTER EFFECT (USED TO DETERMINE f_c)

	Index	Time	X_i	X_{i-1}	X_{i-2}	Y_i	Y_{i-1}	Y_{i-2}
	0	0.00	100	0	0	0.060	0.000	0.000
	1	0.01	100	100	0	0.297	0.060	0.000
	2	0.02	100	100	100	0.754	0.297	0.060
	3	0.03	100	100	100	1.414	0.754	0.297
	4	0.04	100	100	100	2.256	1.414	0.754
	5	0.05	100	100	100	3.264	2.256	1.414
	6	0.06	100	100	100	4.423	3.264	2.256
	7	0.07	100	100	100	5.715	4.423	3.264
	8	0.08	100	100	100	7.128	5.715	4.423
X	9	0.09	100	100	100	8.647	7.128	5.715
X	10	0.10	100	100	100	10.260	8.647	7.128
	11	0.11	100	100	100	11.956	10.260	8.647
	12	0.12	100	100	100	13.723	11.956	10.260
	13	0.13	100	100	100	15.552	13.723	11.956
	14	0.14	100	100	100	17.432	15.552	13.723
	15	0.15	100	100	100	19.355	17.432	15.552
	16	0.16	100	100	100	21.312	19.355	17.432
	17	0.17	100	100	100	23.297	21.312	19.355
	18	0.18	100	100	100	25.301	23.297	21.312
	19	0.19	100	100	100	27.319	25.301	23.297
	20	0.20	100	100	100	29.344	27.319	25.301
	21	0.21	100	100	100	31.372	29.344	27.319
	22	0.22	100	100	100	33.396	31.372	29.344
	23	0.23	100	100	100	35.413	33.396	31.372
	24	0.24	100	100	100	37.417	35.413	33.396
	25	0.25	100	100	100	39.406	37.417	35.413
	26	0.26	100	100	100	41.375	39.406	37.417
	27	0.27	100	100	100	43.322	41.375	39.406
	28	0.28	100	100	100	45.244	43.322	41.375
	29	0.29	100	100	100	47.138	45.244	43.322
	30	0.30	100	100	100	49.001	47.138	45.244
	31	0.31	100	100	100	50.833	49.001	47.138
	32	0.32	100	100	100	52.631	50.833	49.001
	33	0.33	100	100	100	54.394	52.631	50.833
	34	0.34	100	100	100	56.119	54.394	52.631
	35	0.35	100	100	100	57.807	56.119	54.394
	36	0.36	100	100	100	59.457	57.807	56.119
	37	0.37	100	100	100	61.067	59.457	57.807
	38	0.38	100	100	100	62.637	61.067	59.457
	39	0.39	100	100	100	64.166	62.637	61.067
	40	0.40	100	100	100	65.654	64.166	62.637
	41	0.41	100	100	100	67.102	65.654	64.166
	42	0.42	100	100	100	68.508	67.102	65.654
	43	0.43	100	100	100	69.873	68.508	67.102
	44	0.44	100	100	100	71.198	69.873	68.508

TABLE A2—INITIAL SIMULATION OF THE BESSEL FILTER EFFECT (USED TO DETERMINE f_c) (CONTINUED)

Index		Time	X_i	X_{i-1}	X_{i-2}	Y_i	Y_{i-1}	Y_{i-2}
	45	0.45	100	100	100	72.481	71.198	69.873
	46	0.46	100	100	100	73.724	72.481	71.198
	47	0.47	100	100	100	74.927	73.724	72.481
	48	0.48	100	100	100	76.090	74.927	73.724
	49	0.49	100	100	100	77.215	76.090	74.927
	50	0.50	100	100	100	78.300	77.215	76.090
	51	0.51	100	100	100	79.348	78.300	77.215
	52	0.52	100	100	100	80.358	79.348	78.300
	53	0.53	100	100	100	81.331	80.358	79.348
	54	0.54	100	100	100	82.269	81.331	80.358
	55	0.55	100	100	100	83.171	82.269	81.331
	56	0.56	100	100	100	84.039	83.171	82.269
	57	0.57	100	100	100	84.872	84.039	83.171
	58	0.58	100	100	100	85.673	84.872	84.039
	59	0.59	100	100	100	86.442	85.673	84.872
	60	0.60	100	100	100	87.180	86.442	85.673
	61	0.61	100	100	100	87.887	87.180	86.442
	62	0.62	100	100	100	88.564	87.887	87.180
	63	0.63	100	100	100	89.213	88.564	87.887
X	64	0.64	100	100	100	89.834	89.213	88.564
X	65	0.65	100	100	100	90.427	89.834	89.213
	66	0.66	100	100	100	90.994	90.427	89.834
	67	0.67	100	100	100	91.536	90.994	90.427
	68	0.68	100	100	100	92.053	91.536	90.994
	69	0.69	100	100	100	92.546	92.053	91.536
	70	0.70	100	100	100	93.016	92.546	92.053

TABLE A3—FINAL BESSEL COEFFICIENTS

Equation A1	t_F	0.500
Equation A2	f_c	0.6292
Equation A4	B	0.618000
Equation A5	Ω	45.991292
Equation A6	C	0.000729
Equation A7	K	0.905717
	Δt	0.01

TABLE A4—BOUNDARY RESPONSE TIMES (SECOND ITERATION)

$t_{10\%}$	0.09145
$t_{90\%}$	0.5856
$\Delta\ t_{90\%} - t_{10\%}$	0.4951

Table A5 shows a sample calculation for an actual snap-acceleration smoke event collected at 100 Hz. Only 100 (1 s) readings and calculated values are shown so as to reduce the length of the table. The Bessel coefficients shown in Table A3 are used with Equation A8 to calculate the Bessel filter responses (Y_i) to the raw smoke inputs (X_i).

TABLE A5—BESSEL FILTER EXAMPLE

Time	X_i	X_{i-1}	X_{i-2}	Y_i	Y_{i-1}	Y_{i-2}
0.00	0.00	0.00	0.00	0.000	0.000	0.000
0.01	0.00	0.00	0.00	0.000	0.000	0.000
0.02	0.30	0.00	0.00	0.000	0.000	0.000
0.03	0.60	0.30	0.00	0.001	0.000	0.000
0.04	0.50	0.60	0.30	0.004	0.001	0.000
0.05	0.40	0.50	0.60	0.007	0.004	0.001
0.06	0.30	0.40	0.50	0.012	0.007	0.004
0.07	0.10	0.30	0.40	0.017	0.012	0.007
0.08	0.00	0.10	0.30	0.021	0.017	0.012
0.09	0.00	0.00	0.10	0.026	0.021	0.017
0.10	0.00	0.00	0.00	0.029	0.026	0.021
0.11	0.00	0.00	0.00	0.033	0.029	0.026
0.12	0.00	0.00	0.00	0.036	0.033	0.029
0.13	0.20	0.00	0.00	0.039	0.036	0.033
0.14	0.40	0.20	0.00	0.042	0.039	0.036
0.15	0.40	0.40	0.20	0.045	0.042	0.039
0.16	0.30	0.40	0.40	0.049	0.045	0.042
0.17	0.30	0.30	0.40	0.054	0.049	0.045
0.18	0.70	0.30	0.30	0.059	0.054	0.049
0.19	0.80	0.70	0.30	0.066	0.059	0.054
0.20	0.70	0.80	0.70	0.073	0.066	0.059
0.21	0.40	0.70	0.80	0.082	0.073	0.066
0.22	0.20	0.40	0.70	0.091	0.082	0.073
0.23	0.20	0.20	0.40	0.100	0.091	0.082
0.24	0.30	0.20	0.20	0.108	0.100	0.091
0.25	0.50	0.30	0.20	0.116	0.108	0.100
0.26	0.40	0.50	0.30	0.124	0.116	0.108
0.27	0.20	0.40	0.50	0.133	0.124	0.116
0.28	0.00	0.20	0.40	0.140	0.133	0.124
0.29	0.40	0.00	0.20	0.147	0.140	0.133
0.30	0.30	0.40	0.00	0.154	0.147	0.140
0.31	0.20	0.30	0.40	0.161	0.154	0.147
0.32	0.20	0.20	0.30	0.167	0.161	0.154
0.33	0.10	0.20	0.20	0.172	0.167	0.161
0.34	0.10	0.10	0.20	0.177	0.172	0.167
0.35	0.30	0.10	0.10	0.182	0.177	0.172
0.36	0.70	0.30	0.10	0.186	0.182	0.177
0.37	1.10	0.70	0.30	0.192	0.186	0.182
0.38	2.60	1.10	0.70	0.200	0.192	0.186
0.39	3.50	2.60	1.10	0.215	0.200	0.192

TABLE A5—BESSEL FILTER EXAMPLE (CONTINUED)

Time	X_i	X_{i-1}	X_{i-2}	Y_i	Y_{i-1}	Y_{i-2}
0.40	7.10	3.50	2.60	0.239	0.215	0.200
0.41	10.20	7.10	3.50	0.281	0.239	0.215
0.42	15.90	10.20	7.10	0.350	0.281	0.239
0.43	21.80	15.90	10.20	0.458	0.350	0.281
0.44	28.10	21.80	15.90	0.619	0.458	0.350
0.45	34.40	28.10	21.80	0.846	0.619	0.458
0.46	39.90	34.40	28.10	1.149	0.846	0.619
0.47	44.80	39.90	34.40	1.537	1.149	0.846
0.48	50.30	44.80	39.90	2.016	1.537	1.149
0.49	52.70	50.30	44.80	2.590	2.016	1.537
0.50	56.40	52.70	50.30	3.259	2.590	2.016
0.51	58.80	56.40	52.70	4.020	3.259	2.590
0.52	61.50	58.80	56.40	4.873	4.020	3.259
0.53	63.40	61.50	58.80	5.812	4.873	4.020
0.54	64.70	63.40	61.50	6.832	5.812	4.873
0.55	65.00	64.70	63.40	7.928	6.832	5.812
0.56	66.20	65.00	64.70	9.091	7.928	6.832
0.57	66.40	66.20	65.00	10.313	9.091	7.928
0.58	68.30	66.40	66.20	11.589	10.313	9.091
0.59	67.00	68.30	66.40	12.911	11.589	10.313
0.60	66.30	67.00	68.30	14.271	12.911	11.589
0.61	66.40	66.30	67.00	15.659	14.271	12.911
0.62	65.90	66.40	66.30	17.068	15.659	14.271
0.63	66.10	65.90	66.40	18.491	17.068	15.659
0.64	63.50	66.10	65.90	19.921	18.491	17.068
0.65	63.40	63.50	66.10	21.349	19.921	18.491
0.66	61.20	63.40	63.50	22.768	21.349	19.921
0.67	59.90	61.20	63.40	24.170	22.768	21.349
0.68	59.40	59.90	61.20	25.549	24.170	22.768
0.69	58.20	59.40	59.90	26.900	25.549	24.170
0.70	56.60	58.20	59.40	28.218	26.900	25.549
0.71	54.70	56.60	58.20	29.499	28.218	26.900
0.72	53.80	54.70	56.60	30.737	29.499	28.218
0.73	53.40	53.80	54.70	31.930	30.737	29.499
0.74	51.70	53.40	53.80	33.075	31.930	30.737
0.75	50.80	51.70	53.40	34.171	33.075	31.930
0.76	48.80	50.80	51.70	35.214	34.171	33.075
0.77	48.30	48.80	50.80	36.203	35.214	34.171
0.78	45.80	48.30	48.80	37.135	36.203	35.214
0.79	45.30	45.80	48.30	38.009	37.135	36.203
0.80	44.30	45.30	45.80	38.823	38.009	37.135
0.81	42.00	44.30	45.30	39.579	38.823	38.009
0.82	42.20	42.00	44.30	40.274	39.579	38.823
0.83	39.90	42.20	42.00	40.910	40.274	39.579
0.84	39.20	39.90	42.20	41.485	40.910	40.274
0.85	39.10	39.20	39.90	42.002	41.485	40.910
0.86	36.90	39.10	39.20	42.462	42.002	41.485

TABLE A5—BESSEL FILTER EXAMPLE (CONTINUED)

Time	X_i	X_{i-1}	X_{i-2}	Y_i	Y_{i-1}	Y_{i-2}
0.87	36.50	36.90	39.10	42.865	42.462	42.002
0.88	35.20	36.50	36.90	43.211	42.865	42.462
0.89	34.50	35.20	36.50	43.503	43.211	42.865
0.90	34.90	34.50	35.20	43.743	43.503	43.211
0.91	32.70	34.90	34.50	43.934	43.743	43.503
0.92	32.10	32.70	34.90	44.075	43.934	43.743
0.93	31.50	32.10	32.70	44.169	44.075	43.934
0.94	30.50	31.50	32.10	44.216	44.169	44.075
0.95	30.70	30.50	31.50	44.220	44.216	44.169
0.96	30.20	30.70	30.50	44.184	44.220	44.216
0.97	29.30	30.20	30.70	44.110	44.184	44.220
0.98	26.90	29.30	30.20	43.999	44.110	44.184
0.99	25.80	26.90	29.30	43.848	43.999	44.110
1.00	25.30	25.80	26.90	43.660	43.848	43.999

APPENDIX B
CORRECTIONS FOR AMBIENT TEST CONDITIONS

B.1 *Introduction*—Adjustment of snap-acceleration smoke values for the influence of ambient measurement conditions is an important and integral part of the SAE J1667 smoke measurement procedure. Testing has shown at-site ambient environmental conditions to be among the most influential testing factors that affect as-measured snap-acceleration smoke results. The ambient environmental factors incurred at the point of measurement in the form of altitude, barometric pressure, air temperature, and humidity have been combined into the single parameter of dry air density in order to provide a means of accounting for the influence of these factors on snap-acceleration test results. This appendix details procedures and offers guidelines for performing this important adjustment to snap-acceleration smoke values.

As will be summarized in Section B.7, the adjustment equations provided in this appendix were derived from an extensive snap-acceleration smoke test program involving a wide variety of heavy-duty diesel powered vehicles. One of the main conclusions of this test program was that each of the engines powering the test vehicles displayed different degrees of sensitivity to changes in air density. These differences were likely due to the different combustion and smoke control technologies employed by these engines at the time of their manufacture.

The air density adjustment equations provided in this appendix reflect the best fit nominal sensitivity of the sample of engines/vehicles evaluated. Some engines were more sensitive, and some were less sensitive, to the air density changes than predicted by the adjustment equations. In light of this, applying the correction equations to specific engines/vehicles of unknown air density sensitivity, the adjustment equations can only be considered approximate. It is recommended that regulatory agencies adopting this procedure in enforcement programs make some allowance for the fact that the air density sensitivity of individual vehicles tested in the program will, in general, not be known precisely and may be different than indicated by the nominal adjustment.

B.1.1 **Reference Conditions**—To perform an air density adjustment to an observed smoke value, it is necessary to define a reference air density which is used as the basis for the adjustment. The reference dry air density which was selected is:

$$1.1567\ kg/m^3\ (0.0722\ lbm/ft^3)$$

This dry air density is the reference density specified in SAE J1349 and J1995, which specify the net and gross power rating conditions for diesel engines.

B.1.2 **Precautions**

a. The air density extremes encountered during the smoke test program (see Section B.7) used to derive the adjustment equations ranged from a low of 0.908 kg/m^3 (0.0567 lbm/ft^3) to a high of 1.235 kg/m^3 (0.0771 lbm/ft^3). The adjustment equations provided in this appendix should not be used outside of this range of air density.

b. The results from the study used to develop these correction factors suggested that at high temperatures above 32 °C (90 °F) and at low altitude sites around 412 m (1350 ft) in elevation there appeared to be a systematic temperature effect present that may not be accounted for by these correction factors. Residuals (the difference between measured values and calculated values) at these sites tend to decrease in value with increasing temperature. This may suggest the need for further adjustments to the equations to account for these temperature trends.

c. The air density adjustment equations presented here were developed specifically for use with snap-acceleration smoke values obtained using the procedures, equipment, and analysis techniques described in this document. The adjustment equations are not recommended for use with snap-acceleration smoke values obtained using peak-reading type smokemeters, or other smoke measurement procedures.

B.2 Symbols

- A = Final avg. snap-acceleration test result, in units of opacity (%) or smoke density K(m^{-1}), from Equation A4. "A" is equivalent to N_t or K_t, depending on the smoke units being used.
- BARO = Barometric pressure, absolute, kPa (in-Hg).
- c = Regression coefficient for ambient condition adjustment equation.
- DBT = Dry bulb temperature, ambient temperature measured in conjunction with WBT, °C (°F).
- DPT = Dew point temperature, °C (°F).
- F = Ferrel's equation, saturation pressure adjustment factor.
- K = Smoke density (extinction coefficient), per meter (m^{-1}).
- N = Smoke opacity, in percent (%).
- ρ = Air density (dry), kg/m^3 (lbm/ft^3).
- $\Delta\rho$ = Dry air density differential between actual test conditions or reference conditions, and base conditions.
- RH = Relative humidity, percent (%).
- SPT = Water saturation pressure at the ambient temperature, kPa (in-Hg).
- SPWBT = Water saturation pressure at the wet bulb temperature, kPa (in-Hg).
- T = Ambient temperature, if different from the DBT, °C (°F).
- WBT = Wet bulb temperature, °C (°F).
- WVP = Water vapor pressure, kPa (in-Hg).

NOTE—Pressure units given in in-Hg are referenced to 0 °C.

subscripts

- abs = absolute temperature. T + 273.15 Kelvin (T + 459.67 °R)
- base = base dry air density. The air density upon which the ambient conditions correction regression coefficients are based.
- ref = at reference dry air density conditions, 1.1567 kg/m^3 (0.0722 lbm/ft^3).
- t = at non-reference dry air density, usually actual test dry air density.

B.3 Snap-Acceleration Smoke Adjustment Methods—This appendix contains snap-acceleration adjustment equations that account for the air density effects on snap-acceleration smoke. The measured vehicle smoke value (A) is adjusted to the reference air density (ρ_{ref}). The measured smoke value (A), along with the actual dry air density (ρ_t) at the time of the test, are used in Section B.4 for opacity units or Section B.5 for smoke density units to compute the smoke level (N_{ref} or K_{ref}) at the reference air density (ρ_{ref}).

B.4 Adjustment of Snap-Acceleration Smoke Opacity (N) Values for the Effects of Changes in the Dry Air Density—The approach for adjusting smoke opacity values for the effects of changes in the dry air density is to convert the smoke opacity value, N_t, to smoke density units (K), adjust the smoke density value according to the procedures described in Section B.5, and then re-convert the adjusted smoke density value back into smoke opacity units as N_{ref}.

To adjust a snap-acceleration smoke opacity value for the effects of changes in the dry air density:

1. Convert the smoke opacity value to the equivalent smoke density units using the following equation:

$$K = (-1/L) \cdot \ln(1 - (N/100)) \quad \text{(Eq.B1)}$$

where:

K = Smoke density (m^{-1}).
L = Optical path length of the smoke measurement, in meters (m). If L is not known, assume a value of 0.127 m.
N = Smoke opacity value to be converted, usually N_t.

2. Adjust the resulting smoke density value, calculated in step 1, according to the procedures described in Section B.5 to produce K_{ref}.

3. Convert the resulting adjusted smoke density value calculated in Section B.5 to equivalent smoke opacity units according to the following equation:

$$N = (1 - e^{-KL}) \cdot 100 \quad \text{(Eq.B2)}$$

where:

N = Ambient conditions adjusted smoke opacity value, N_{ref}.
K = Ambient conditions adjusted smoke density value, K_{ref}, determined in Section B.5.
L = Optical path length value used in Equation B1.

NOTE—It is important to use the same value of L (optical path length) for the conversion to smoke density units and for the re-conversion back to smoke opacity units. The actual value of L is not critical; however, it must be a positive non-zero value.

B.5 Adjustment of Snap-Acceleration Smoke Density (K) Values for the Effects of Changes in the Dry Air Density—The base air density (ρ_{base}) parameter used in this section should not be confused with the reference air density (ρ_{ref}). The base air density is the ambient condition used to develop the adjustment regression coefficient used in this section. The adjustment equations in this section provide for the reference air density to be different from the base air density used in the regression analysis of the ambient conditions test data.

To adjust a measured snap-acceleration smoke density value to reference air density conditions:

1. Calculate the air density differences using ρ_{ref} and ρ_{base}:

$$\Delta\rho_1 = \rho_{ref} - \rho_{base} \qquad \text{(Eq.B3)}$$

$$\Delta\rho_2 = \rho_t - \rho_{base} \qquad \text{(Eq.B4)}$$

2. Calculate the adjusted snap-acceleration smoke density value, K_{ref}, at the reference dry air density, using Equation B5, and the appropriate values for coefficient c and r from Table B1.

$$K_{ref} = K_t \cdot \frac{\left(c \cdot \Delta\rho_1^2 + 1\right)}{\left(c \cdot \Delta\rho_2^2 + 1\right)} \qquad \text{(Eq.B5)}$$

TABLE B1—SMOKE DENSITY ADJUSTMENT CONSTANTS

Air Density Units	c	ρ_{base}	
kg/m^3	21.1234	1.2094	(metric)
lbm/ft^3	5420.0671	0.0755	(English)

3. Substituting the values in Table B1 for c and ρ into Equation B3 through B5 produces Equation B6 and B7 for K_{ref}.

Metric Units ρ (kg/m^3)

$$K_{ref} = \frac{K_t}{19.952\,\rho_t^2 - 48.259\,\rho_t + 30.126} \qquad \text{(Eq.B6)}$$

English Units ρ (lbm/ft^3)

$$K_{ref} = \frac{K_t}{5119.55\,\rho_t^2 - 773.05\,\rho_t + 30.126} \qquad \text{(Eq.B7)}$$

B.6 Calculation of Dry Air Density—In order to correct the smoke values using the equations in Sections B.4 or B.5, it is first necessary to determine the dry air density at the test conditions. This can be done by measuring the barometric pressure (BARO), the ambient air temperature (T or DBT), and either the dew point temperature (DPT), or the wet and dry bulb temperatures (WBT and DBT), or the relative humidity (RH). From these measurements the dry air density may be determined from the following equation.

$$\rho = (u * (BARO - WVP))/(T_{abs}) \qquad \text{(Eq.B8)}$$

where:

TABLE B2

	Metric	English
ρ, Air Density (dry)	kg/m^3	lbm/ft^3
Units conversion (u)	3.4836	1.3255
Barometric Pressure (BARO)	kPa	in-Hg
Water Vapor Pressure (WVP)	kPa	in-Hg
Ambient Temperature (T_{abs})	Kelvin	°R

The barometric pressure and the ambient temperature must be measured at the test conditions of interest. The water vapor pressure may be calculated as described in B.6.1, or obtained from a psychrometric chart.

NOTE—Exclusion of the water vapor pressure term in Equation B8 (calculation of dry air density) is permissible, thus eliminating the need to measure DPT, WBT, or RH and calculate the WVP. However, the user should be aware that this results in a bias error, usually towards a smaller adjustment factor applied to the smoke values. In addition, it should be noted that as the ambient temperature increases, the amount of water the air can hold increases rapidly, and thus, the potential impact of this error also increases. The examples in Section B.6 illustrate the impact of ignoring the water vapor pressure in the adjustment equations.

B.6.1 Calculation of Water Vapor Pressure (WVP)—The method of calculating the water vapor pressure is dependent upon the instrumentation used to determine the moisture in the ambient air. The most common methods utilized are by the measurement of the dew point temperature (DPT), the measurement of the wet bulb/dry bulb temperatures, and by the measurement of the relative humidity (RH). From these measurements, the vapor pressure of the air may be determined.

B.6.1.1 CALCULATION OF WVP FROM DEW POINT TEMPERATURE—This procedure uses a dimensionless (normalized) polynomial for the vapor pressure calculation. This allows calculations to be performed in any units, utilizing the same polynomial coefficients. In using this technique, the input and output parameters to the polynomial are normalized and un-normalized, respectively, with the supplied support equations.

a. Calculate the normalized dew point temperature (NT) from the measured dew point temperature (DPT).

$$NT = (DPT - TL)/(TH - TL) \qquad \text{(Eq.B9)}$$

TABLE B3

Temperature Units	TL	TH
°C	−30.0	+40.0
°F	−22.0	+104.0

NOTE—DPT, TL, and TH must be in the same temperature units. Equation B9 applies over a dew point temperature range of −30 to +40 °C (−22 to +104 °F).

b. Calculate the normalized water vapor pressure (NP) at the normalized dew point temperature (NT).

$$\begin{aligned} NP = &-4.959658E\text{-}5 + (4.956773E\text{-}2 * NT) \\ &+ (9.455172E\text{-}2 * NT^2) + (4.199096E\text{-}1 * NT^3) \\ &+ (-7.549164E\text{-}2 * NT^4) + (5.114628E\text{-}1 * NT^5) \end{aligned} \qquad \text{(Eq.B10)}$$

c. Un-normalize the saturation pressure (NP) to produce the WVP at the dew point temperature, DPT, in the units of choice.

$$WVP = PL + (NP * (PH - PL)) \qquad \text{(Eq.B11)}$$

TABLE B4

Pressure Units	PL	PH
kPa	5.0951E-2	7.375
in-Hg	1.5046E-2	2.178

NOTE—WVP, PL, and PH must be in the same pressure units.

B.6.1.2 CALCULATION OF WVP FROM WET BULB/DRY BULB TEMPERATURES—This procedure uses a dimensionless (normalized) polynomial for the vapor pressure calculation. This allows calculations to be performed in any units, utilizing the same polynomial coefficients. In using this technique, the input and output parameters to the polynomial are normalized and un-normalized, respectively, with the supplied support equations.

a. Calculate the normalized wet bulb temperature (NT) from the measured wet bulb temperature (WBT).

$$NT = (WBT - TL)/(TH - TL) \qquad \text{(Eq.B12)}$$

TABLE B5

Temperature Units	TL	TH
°C	−30.0	+40.0
°F	−22.0	+104.0

NOTE—WBT, TL, and TH must be in the same temperature units. Equation B12 applies over a wet bulb temperature range of –30 to +40 °C (–22 to +104 °F).

b. Calculate the normalized saturation pressure (NP) at the normalized wet bulb temperature (NT).

$$\begin{aligned} NP = &-4.959658E\text{-}5 + (4.956773E\text{-}2 * NT) \\ &+ (9.455172E\text{-}2 * NT^2) + (4.199096E\text{-}1 * NT^3) \\ &+ (-7.549164E\text{-}2 * NT^4) + (5.114628E\text{-}1 * NT^5) \end{aligned} \qquad \text{(Eq.B13)}$$

c. Un-normalize the saturation pressure (NP) to produce the saturation pressure at the wet bulb temperature, SPWBT, in the units of choice.

$$SPWBT = PL + (NP * (PH - PL)) \qquad \text{(Eq.B14)}$$

TABLE B6

Pressure Units	PL	PH
kPa	5.0951E-2	7.375
in-Hg	1.5046E-2	2.178

NOTE—SPWBT, PL, and PH must be in the same pressure units.

d. Using Ferrel's equation, calculate the adjustment factor (F).

Metric Units—WBT in °C

$$F = 3.67E\text{-}4 * (1 + (1.152E\text{-}3 * WBT)) \qquad \text{(Eq.B15)}$$

English Units—WBT in °F

$$F = 3.67E\text{-}4 * (1 + (6.4E\text{-}4 * (WBT - 32))) \qquad \text{(Eq.B16)}$$

e. Calculate the Water Vapor Pressure (WVP).

Metric Units—SPWBT, BARO in kPa; DBT, WBT in °C.

$$WVP = SPWBT - (1.8 * F * BARO * (DBT - WBT)) \qquad \text{(Eq.B17)}$$

English Units—SPWB, BARO in in-Hg; DBT, WBT in °F.

$$WVP = SPWBT - (F * BARO * (DBT - WBT)) \qquad \text{(Eq.B18)}$$

B.6.1.3 CALCULATION OF WVP FROM RELATIVE HUMIDITY AND AMBIENT TEMPERATURE—This procedure uses a dimensionless (normalized) polynomial for the vapor pressure calculation. This allows calculations to be performed in any units, utilizing the same polynomial coefficients. In using this technique, the input and output parameters to the polynomial are normalized and un-normalized, respectively, with the supplied support equations.

a. Calculate the normalized ambient temperature (NT) from the measured ambient temperature (T).

$$NT = (T - TL)/(TH - TL) \qquad \text{(Eq.B19)}$$

TABLE B7

Temperature Units	TL	TH
°C	−30.0	+40.0
°F	−22.0	+104.0

NOTE—T, TL, and TH must be in the same temperature units. Equation B19 applies over an ambient temperature range of −30 to +40 °C (−22 to +104 °F).

b. Calculate the normalized saturation pressure (NP) at the normalized ambient temperature (NT).

$$\begin{aligned} NP = {} & -4.959658E\text{-}5 + (4.956773E\text{-}2 * NT) \\ & + (9.455172E\text{-}2 * NT^2) + (4.199096E\text{-}1 * NT^3) \\ & + (-7.54916E\text{-}2 * NT^4) + (5.114628E\text{-}1 * NT^5) \end{aligned} \qquad \text{(Eq.B20)}$$

c. Un-normalize the saturation pressure (NP) to produce the saturation pressure at the ambient temperature, SPT, in the units of choice.

$$SPT = PL + (NP * (PH - PL)) \qquad \text{(Eq.B21)}$$

TABLE B8

Pressure Units	PL	PH
kPa	5.0951E-2	7.375
in-Hg	1.5046E-2	2.178

NOTE—SPT, PL, and PH must be in the same pressure units.

d. Calculate the WVP at the measured relative humidity, RH. WVP will be in the same units as SPT.

$$WVP = SPT * (RH/100) \qquad \text{(Eq.B22)}$$

B.7 Examples of Adjustments to Ambient Smoke Values—The following hypothetical examples may assist in applying the ambient correction equations. Both metric and English unit based examples are provided. Also included for reference are the applicable equation numbers used in this appendix.

Example 1

Situation—A vehicle tested for smoke at a moderate elevation produces an average snap-acceleration smoke value of 60% opacity (the (A) value reported from Equation B3).

Task—From the ambient conditions measurements, determine the adjusted smoke opacity (N_{ref}) at the reference air density (ρ_{ref}).

Ambient measurements	Equation Constants
Smoke (A) = 60% opacity	c = 54.200671
(BARO) = 27.00 in-Hg	TL = −22 °F
(T) = 77 °F	TH = 104 °F
(RH) = 50%	PL = 1.5046E-2 in-Hg
	PH = 2.178 in-Hg
	EOPL = 0.127 m
	(ρ_{ref}) = 0.0722 lbm/ft^3
	(ρ_{base}) = 0.0755 lbm/ft^3

Calculations:

(Eq.B19) NT = (77 − (−22))/(104 − (−22)) = 0.785714
(Eq.B20) NP = 0.425334 (polynomial)
(Eq.B21) SPT = 1.5046E-2 + 0.425334 * (2.178 − 1.5046E-2)
= 0.935024
(Eq.B22) WVP = 0.935024 * (50.0/100)
= 0.4675
(Eq.B8) ρ_{dry} = (1.3255 * (27.0 − 0.4675))/(77 + 459.67)
= 0.06553
(Eq.B1) K_t = 7.215
(Eq.B3) $\Delta\rho_1$ = 0.0722 − 0.0755 = −0.0033
(Eq.B4) $\Delta\rho_2$ = 0.06553 − 0.0755 = −0.00996
(Eq.B5) K_{ref} = 4.966
(Eq.B2) N_{ref} = 46.8%

Result—A vehicle with a snap-acceleration smoke level of 60% opacity at a dry air density of 0.0655 lbm/ft^3 would be projected to produce a smoke value of 46.8% opacity at the reference dry air density of 0.0722 lbm/ft^3.

It should be noted that if the RH measurement had not been performed and the effect of WVP ignored, the resulting impact would have changed N_{ref} from 46.8% to 49.5% opacity.

Example 2

Situation—A vehicle tested for smoke at a moderate elevation produces an average snap-acceleration smoke density of 7.2 m^{-1} (the (A) value reported from Equation B3).

Task—From the ambient conditions measurements, determine the adjusted smoke density (K_{ref}) at the reference air density (ρ_{ref}).

Ambient measurements	Equation Constants
Smoke (A) = 7.2 m^{-1}	c = 0.211234
(BARO) = 88.50 kPa	TL = −30 °C
(T) = 20 °C	TH = 40 °C
(DPT) = 10 °C	PL = 5.0951E-2 kPa
	PH = 7.375 kPa
	(ρ_{ref}) = 1.1567 kg/m^3
	(ρ_{base}) = 1.2094 kg/m^3

Calculations:

(Eq.B9) NT = (10 − (−30))/(40 − (−30)) = 0.571428

(Eq.B10) NP = 0.160612 (polynomial)

(Eq.B11) WVP = 5.0951E-2 − (0.160612 * (7.375 − 5.0951E-2)) = 1.2272

(Eq.B8) ρ_{dry} = (3.4836 * (88.5 − 1.227))/(20 + 273.15) = 1.0370

(Eq.B3) $\Delta\rho_1$ = 1.1567 − 1.2094 = −0.0527

(Eq.B4) $\Delta\rho_2$ = 1.0370 − 1.2094 = −0.17230

(Eq.B5) K_{ref} = 4.684 m^{-1}

Result—A vehicle with a snap-acceleration smoke density of 7.2 m^{-1} at a dry air density of 1.0370 kg/m^3 would be projected to produce a smoke density of 4.684 (m^{-1}) at the reference dry air density of 1.1567 kg/m^3.

B.8 Snap-Acceleration/Air Density Field Test Program—The snap-acceleration smoke adjustment equations of this appendix were derived using data from a smoke test program designed to study the effects of ambient conditions on snap-acceleration smoke levels. The test program was conducted during the summer of 1993 and involved measuring the snap-acceleration levels of several heavy-duty diesel-powered vehicles, as the vehicles traveled an out and back route over a wide range of elevations on Interstate 80, in California. The vehicles were tested for snap-acceleration smoke with several types of smokemeters using the SAE J1667 test procedures and data analysis algorithm. Eight tests were performed at six different elevations along the route. At two of the elevations, tests were performed on both the outbound and return legs of the test route. The range of the ambient test conditions encountered during the test program are shown in Table B9.

TABLE B9—TEST PROGRAM AMBIENT EXTREMES

Units	min	max
Metric		
Elevation	12 m	2207 m
Air Density (dry)	0.906 kg/m^3	1.235 kg/m^3
Air Density (wet)	0.915 kg/m^3	1.240 kg/m^3
Barometer	78.3 kPa	101.7 kPa
Ambient Temp.	11.7 °C	37.2 °C
Specific Humidity	0.6 gm/kg	12.7 gm/kg
English		
Elevation	40 ft	7240 ft
Air Density (dry)	0.0567 lbm/ft^3	0.0771 lbm/ft^3
Air Density (wet)	0.0571 lbm/ft^3	0.0774 lbm/ft^3
Barometer	23.11 in-Hg	30.03 in-Hg
Ambient Temp.	53 °F	99 °F
Specific Humidity	4 grains	89 grains

A total of 24 diesel-powered vehicles were tested in the program, with the number, type, and manufacturer of the diesel engines powering these vehicles providing a fairly representative sample of the engines in the general U.S. heavy-duty vehicle population. Engines manufactured by Caterpillar, Cummins, Detroit Diesel (both 2 and 4 cycle), and Mack were included in the test sample, as were engines with both mechanical and electronic injection control systems. There was one naturally aspirated engine in the test sample with the rest being turbocharged. The manufacturing dates of the engines covered a range from 1971 to 1993 with about 46% of the engines manufactured in the 1985-1989 period and about 33% manufactured between 1990 and 1993.

Four different manufacturers of smokemeters (Bosch, Caltest, Sun, and Wager) participated in the test program. The smokemeters included full flow end-of-line (EOL) and sampling type smokemeters. Both peak-reading meters and prototype meters which were programmed to perform the SAE J1667 half-second averaging algorithm were included in the testing.

The data from the testing program were assembled into a single data base so that standard mathematical and statistical procedures could be utilized to query for relationships among the various test parameters. Data from the peak-reading meters and data which did not meet the SAE J1667 test validation criteria, as given in 5.4.4, were excluded from the analyses. Dry air density, barometric pressure, and altitude all produced significant correlations with the snap-acceleration smoke values, with dry air density providing the better correlation.

The data from this test program were also used to quantify the repeatability of the test procedure. This was done in two ways. In the first method, the average of the ambient condition corrected smoke values was computed for each vehicle, test day and smokemeter combination. The deviations of the individual corrected smoke values from this average were then computed and used to provide a measure of the repeatability of the test procedure over the full range of ambient conditions encountered in the test program and allowed by the procedure. When this was done for all the data in the test program data base, 91% of the deviations from average were less than 6% opacity.

In the second method, only the data taken at the two elevations where repeat tests were run were utilized. For each vehicle/meter combination the two test results obtained at these test locations created a data pair which differed only slightly in ambient dry air density. (Since the elevation was the same for both points in the data pair, the only source of air density differences was the change in ambient conditions which occurred in the few hours between the two tests.) All these smoke values were corrected to the standard reference air density using the methods described in this appendix and the deviation of the corrected smoke values was noted for each data pair. For 90% of the pairs, the deviations were less than 3% opacity.

The difference in the repeatabilities quantified by the two methods reflects the imprecision of applying the ambient condition corrections to specific vehicles over wide ranges of air density.

APPENDIX C
APPLICATION OF CORRECTIONS TO MEASURED SMOKE VALUES

.1 *Introduction*—Fundamentally, all smoke opacimeters measure the transmittance of light through a smoke plume or a sample of gas which contains smoke particles. Typically, however, it is desired to quantify and report the exhaust smoke emissions in units of either smoke opacity (N) or smoke density (k). Furthermore, if the smoke level is reported as smoke opacity, then is it also necessary to report the associated effective optical path length to fully specify the smoke level of the vehicle. This is because measured smoke opacity is a function of the effective optical path length (EOPL) used to make the measurement. For example, an engine that yielded a 20% opacity when tested with a tailpipe which caused the EOPL to be 76 mm would have measured opacities of 26%, 31%, and 36%, respectively, when tested with larger tailpipes which caused the EOPL to be 102, 127, and 152 mm. Therefore, to facilitate comparisons of smoke opacity data from different sources and with smoke standards which may be developed, opacity values must be reported at standard effective optical path lengths.

When smoke is measured using an effective optical path length which is different than the standard path length, the measured smoke values must be converted to opacity at the standard path length using the appropriate Beer-Lambert relationship. Similarly, if it is desired to report the test results in units of smoke density, it is necessary to use the Beer-Lambert relationship to convert the measured opacity results to smoke density.

Finally, if smoke measurements are made using a smokemeter having a red LED light source, a wavelength correction is necessary to account for the fact that the ability of diesel smoke to absorb light depends on the wavelength of the light.

This appendix describes how measured smoke values are to be corrected to the desired reporting units using the Beer-Lambert relationships and how the light source wavelength corrections are to be made.

.2 *Definitions and Symbols*

2.1 **Diesel Smoke**—Particles, including aerosols, suspended in the exhaust stream of a diesel engine which absorb, reflect, or refract light.

2.2 **Transmittance (T)**—The fraction of light transmitted from a source which reaches a light detector.

2.3 **Opacity (N)**—The percentage of light transmitted from a source which is prevented from reaching a light detector.

2.4 **Effective Optical Path Length (L)**—The length of the smoke obscured optical path between the smokemeter light source and light detector. Note that portions of the total light source to detector path length which are not smoke obscured do not contribute to the effective optical path length.

2.5 **Smoke Density (k)**—A fundamental means of quantifying the ability of a smoke plume or a smoke-containing gas sample to prevent the passage of light. By convention, smoke density is expressed on a per meter basis (m^{-1}).

2.6 **W**—The wavelength of the smokemeter light source.

C.2.7 Subscripts

C.2.7.1 m—Refers to the as-measured condition

C.2.7.2 s—Refers to values corrected to a standard condition

C.3 Beer-Lambert Relationships—The Beer-Lambert Law defines the relationship between transmittance, smoke density, and effective optical path length as shown in Equation C1.

$$T = e^{-kL} \quad \text{(Eq.C1)}$$

From the definitions of transmittance and opacity, the relationship between these parameters may be defined as shown in Equation C2.

$$N\ (\%) = 100 * (1 - T) \quad \text{(Eq.C2)}$$

From Equations C1 and C2 the following important relationships can be derived:

$$N_s = 100 * (1 - ((1 - (N_m/100))(L_s/L_m))) \quad \text{(Eq.C3)}$$

$$k = -(1/L_m) * (1n\ (1 - (N_m/100))) \quad \text{(Eq.C4)}$$

To achieve proper results in applying Equations C1 and C4, the effective optical path lengths (L and L_m) must be expressed in units of meters (m). It is recommended that the effective optical path lengths used in Equation C3 also be expressed in meters (m); however, any length unit may be used as long as L_s and L_m are expressed in the same measurement unit.

C.4 Use of Beer-Lambert Relationships—Conversion from as-measured smoke values to appropriate reporting units is a two-step process. Since, as noted in Section C.1, the basic measurement unit of all smokemeters is transmittance, the first step in all cases is to convert from transmittance (T) to opacity at the as-measured effective optical path length (N_m) using Equation C2. Since all opacimeters do this internally, this step is transparent to the user.

The second step of the process is to convert from N_m to the desired reporting units as follows:

a. If the test results are to be reported in opacity units, Equation C3 must be used to convert from opacity at the as-measured effective optical path length to opacity at the standard effective optical path length. (In the event that the measured and standard effective optical path lengths are identical, N_s is equal to N_m and this secondary conversion step is not required.)

b. If the test results are to be reported in units of smoke density, then Equation C4 must be applied.

C.5 Effective Optical Path Length Input Values—In order to apply conversion Equation C4, it is necessary to input the as-measured effective optical path length (L_m). To use Equation C3, values must be input both for L_m and for L_s, the standard effective optical path length. This section provides guidance on the determination of these input values.

C.5.1 Determination of L_m—For full-flow end-of-line type smokemeters, L_m is a function of the vehicle tailpipe design. For straight tailpipes with a circular cross section, L_m is equal to the tailpipe ID. For tailpipes constructed of common tubing, the tubing OD may be used to approximate the tubing ID. Appendix D provides guidance in determining L_m for other tailpipe configurations.

For sampling type smokemeters, L_m is a fixed function of the meter measurement cell and purge air system design. Specification data supplied by the meter manufacturer should be consulted to determine the appropriate value for L_m when this type of smokemeter is used.

Typically, it is necessary to determine L_m within ±5 mm to achieve corrected smoke results that are accurate within ±2% opacity or ±0.2 m^{-1} smoke density.

C.5.2 Determination of L_s—To ensure meaningful smoke data comparisons, smoke opacity results should be reported at the standard effective optical path lengths, L_s, shown in Table C1. Table C1 is constructed such that the standard effective optical path length increases with the engine power rating and approximates exhaust tailpipe sizes commonly used in vehicle applications. In cases where the engine rated power cannot be determined, the actual tailpipe OD usually provides a good approximation of L_s and may be used in lieu of Table C1.

TABLE C1—STANDARD EFFECTIVE OPTICAL PATH LENGTHS

Rated Engine Power kW	Rated Engine Power BHP	Standard Effective Optical Path Length mm	Standard Effective Optical Path Length in
Less than 75	Less than 101	51	2
75 to 149	101 to 200	76	3
150 to 224	201 to 300	102	4
225 or More	301 or more	127	5

When testing vehicles with multiple exhaust outlets, the total rated engine power must be used with Table C1 to determine the standard effective optical path length. The rated engine power must not be divided by the number of exhaust outlets when using Table C1. If this error is made, it will result in reported smoke opacity values which are erroneously low.

C.6 Sequencing of Beer-Lambert Corrections

C.6.1 Preferred Method—To achieve the highest degree of accuracy, the Beer-Lambert conversion calculations described in Section C.4 should be performed on each instantaneous measured smoke value before any further data-processing takes place. To perform the calculations in this manner during snap-acceleration testing requires significant data-processing capacity since the minimum smoke data-processing rate is 20 Hz. In addition, the ability to input values for L_m and L_s to the data-processing unit is required.

C.6.2 Alternate Methods—In some cases, users may wish to use data-processing systems which are not capable of performing the Beer-Lambert corrections using the preferred method in C.6.1. In these cases, either of the following alternate techniques may be employed; however, users are cautioned that there will be some loss of accuracy.

a. The appropriate Beer-Lambert conversion equations as defined in Section C.4 may be applied after instantaneous smoke values have been averaged using the procedures described in Appendix A. The snap-acceleration test error that results from the use of this method will, in most cases, be less than 1% opacity or 0.15 m^{-1} smoke density, but could be somewhat higher when the snap-acceleration test generates a very high and sharp smoke spike.

b. Appropriate Beer-Lambert conversions may be performed manually on as-measured average smoke values by using the alignment chart shown in Figure C1. In this method, an as-measured smoke opacity (N_m) is located on the vertical column which most closely represents the as-measured effective optical path length (L_m). The user then reads horizontally across the chart to the column which represents the standard effective optical path length (L_s) if a smoke opacity output is desired, or to the smoke density column if a density output is desired. The user then reads the desired output by interpolating the scale of the target column. For example, if an opacity value of 40% were measured using an effective optical path length of 102 mm (4 in), the chart could be used to determine that the equivalent opacity at a path length of 127 mm (5 in) is approximately 47% and that the associated smoke density is about 5.0 m^{-1}.

Since the alignment chart was developed using Equations C3 and C4, the fundamental accuracy of this method is the same as alternate method (a). However, when the as-measured effective optical path length is not equal to one of the values which appear as one of the vertical chart scales the utility and/or accuracy of this method is reduced. This method also introduces the potential for small errors due to resolution and readability of the non-linear chart scales.

C.7 Smokemeter Light Source Wavelength Corrections—The ability of diesel smoke to absorb light is wavelength dependent (i.e., diesel smoke does not have neutral spectral density). For this reason, smokemeters using different light sources will respond differently to the same smoke sample, and corrections are required to achieve comparable results.

Since most smokemeters today use either a green LED or an incandescent light source, with an equivalent peak spectral emissivity, this will be the standard for reporting snap-acceleration test results. Smoke measurements made with meters using red LED light sources must be corrected using the following equations.

$$N_s = 100 * (1 - ((1 - (N_m/100))(w_m/w_s))) \quad \text{(Eq.C5)}$$

$$K_s = (-1/L) * 1n((1 - (N_m/100))(w_m/w_s)) \quad \text{(Eq.C6)}$$

where:

W_s = the wavelength of a standard green LED light source = 570 nm
W_m = the wavelength of a red LED light source = 660 nm

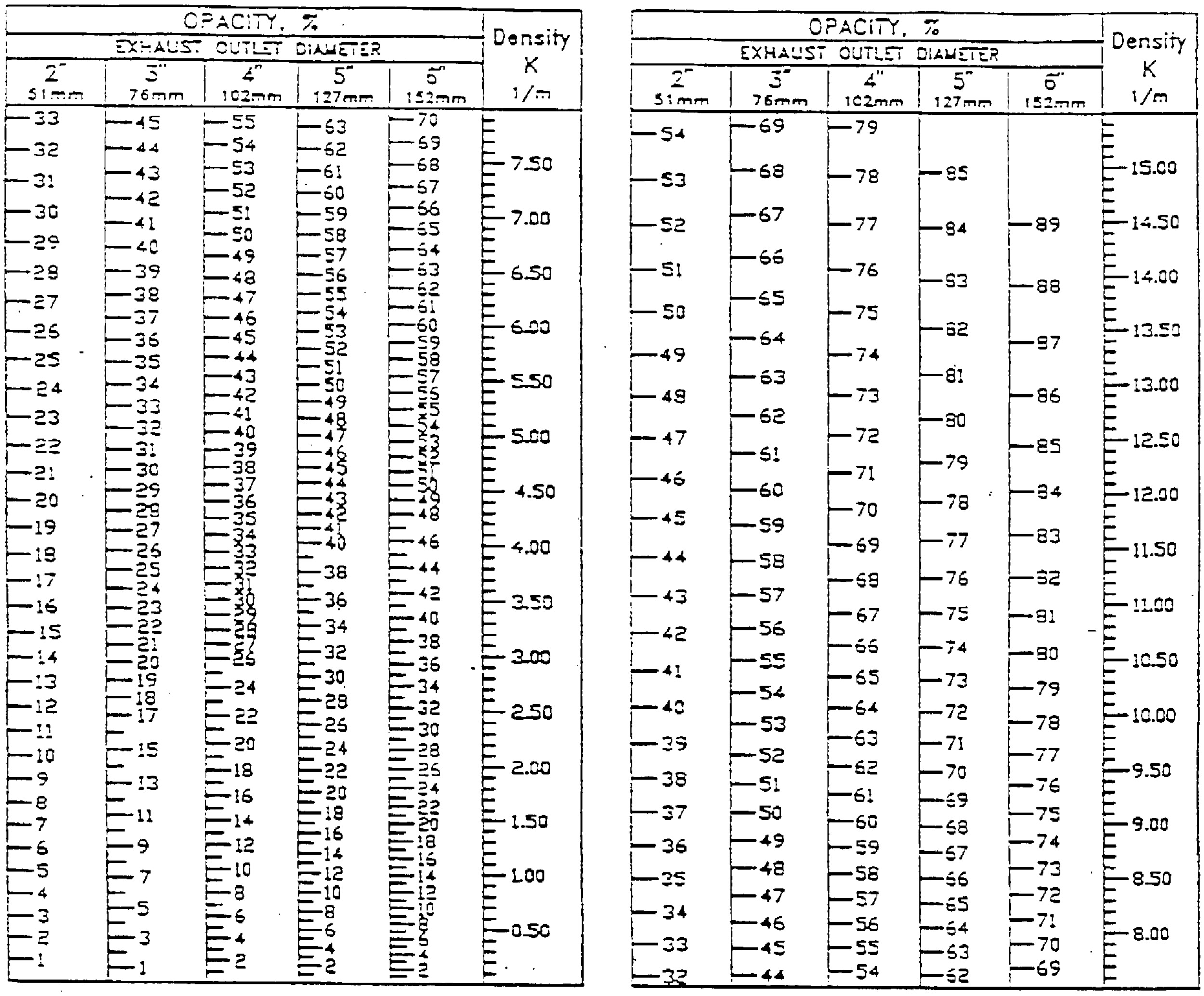


FIGURE C1—ALIGNMENT CHART

It is preferred that the wavelength corrections, like the Beer-Lambert corrections, be applied to each instantaneous measured smoke value. However, if this is not possible, and if small errors are acceptable, the wavelength corrections may be applied after average smoke values are obtained as described in Appendix A.

Light source wavelength corrections using Equations C5 and C6 should be applied when the meter is used to measure diesel smoke, but should not be used when the meter is being calibrated using a neutral density filter.

APPENDIX D
EXHAUST SYSTEMS AND SPECIAL APPLICATIONS

D.1 Introduction—In order to report snap-acceleration test results at standard conditions, the Beer-Lambert effective optical path length corrections described in Appendix C must be applied to the as-measured smoke values. A required input for the Beer-Lambert corrections is the as-measured effective optical path length (L_m). When a sampling type smokemeter is used, L_m is a function of the meter design and is expected to be supplied by the meter manufacturer. When a full-flow end-of-line smokemeter is used, L_m is a function of the vehicle exhaust system and the way the meter is mounted on the tailpipe. Users of full-flow smokemeters must, therefore, determine L_m for each test conducted on a case by case basis.

Recognizing the wide variety of exhaust systems that may be encountered when conducting vehicle tests, this appendix provides guidelines which will assist full-flow smokemeter users in determining L_m. This appendix also includes suggestions for mounting full-flow meters on specific types of vehicular exhaust systems. Following these suggestions will facilitate the determination of L_m and will insure that proper smoke measurement principles are adhered to.

D.2 Determination of the As-Measured Effective Optical Path Length (L_m)

D.2.1 General Comments—The effective optical path length has been defined as "the length of the smoke obscured path between the smokemeter light source and detector." Portions of the light source to detector path length which are not smoke obscured do not contribute to the effective optical path length. If the smokemeter light beam is located sufficiently close to the exhaust outlet (within 7 cm or 2.76 in) the cross section of the smoke plume as it passes by the smokemeter is essentially the same as the tailpipe outlet and the effective optical path length is equal to the internal distance across the tailpipe outlet along the line of orientation of the smokemeter light beam. In general, this distance should be determined by direct measurement of the tailpipe outlet, and to achieve corrected smoke results which are within ±2% opacity or ±0.2 m^{-1} smoke density, this measurement should be made within ±5 mm (±0.197 in).

It is often difficult, particularly in roadside testing applications, to gain access to and obtain direct measurements of the tailpipe outlets on many vehicles. Fortunately, for many common tailpipe designs L_m can be determined with sufficient accuracy from external exhaust system dimensions which are more easily measured. The remainder of this section describes these cases and the principles and procedures that should be adhered to in determining L_m.

D.2.2 External Versus Internal Tailpipe Dimensions—Most tailpipes encountered on vehicles are constructed from metal tubing of various standard nominal sizes. Nominal tubing sizes are based on the tubing OD whereas it is the internal dimension of the tailpipe that dictates L_m. The difference between the external and internal tailpipe dimension is twice the tubing wall thickness which is typically about 1.5 mm (0.060 in).

Use of the external tailpipe dimension as the as-measured effective optical path length results in corrected smoke values which are slightly less than the true corrected smoke values (~1% opacity or 0.01 m^{-1} smoke density). In most cases, this small error is acceptable. However, in cases where extreme accuracy is required or where the tailpipe wall thickness is unusually large, the material thickness should be accounted for in determining L_m.

D.2.3 **Straight Circular Non-Beveled Tailpipes**—This is the simplest tailpipe design that may be encountered and is illustrated in Figure D1. In this case, the smokemeter light beam should be oriented such that it is perpendicular to and passes through the central axis of the smoke plume and is within 70 mm (2.76 in) of the tailpipe exit. If these guidelines are followed, L_m is equal to the tailpipe ID and can usually be adequately approximated by the tailpipe OD (see D.2.2).

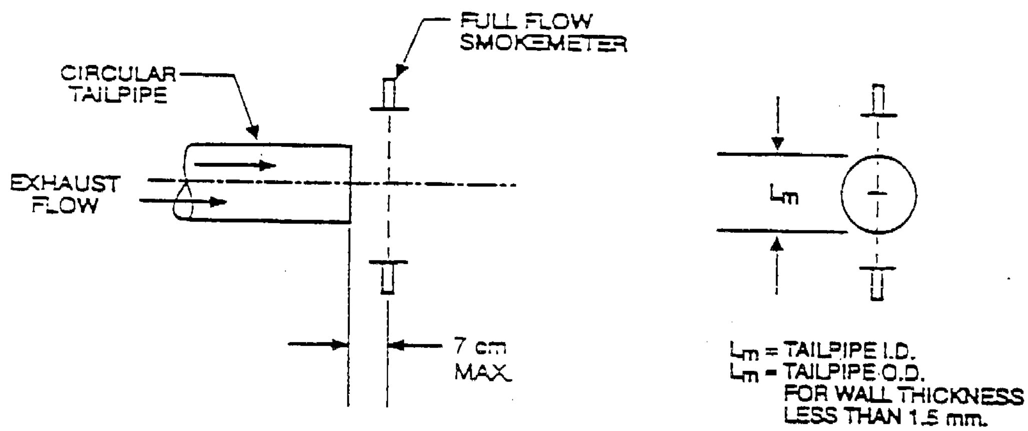


FIGURE D1—STRAIGHT CIRCULAR NON-BEVELED TAILPIPE

D.2.4 **Straight Circular Beveled Tailpipes**—A beveled tailpipe is formed when the outlet of the tailpipe is not cut off square (perpendicular) to the axis of the exhaust flow. When this type of tailpipe is encountered, there is only one recommended smokemeter mounting orientation. The axis of the smokemeter light beam should be perpendicular to and passing through the central axis of the smoke plume and should be parallel to the minor axis of the elliptical shape of the tailpipe exit. The smokemeter light beam must also be within 70 mm (2.76 in) of the tailpipe outlet (Figure D2). If these guidelines are followed, L_m is equal to the tailpipe ID and can usually be adequately approximated by the tailpipe OD (see D.2.2).

D.2.5 **Curved Circular Tailpipes**—When the central axis of the tailpipe is curved at the approach to the exit, the tailpipe is said to be curved and the cross section of the tailpipe outlet is non-circular. To avoid erroneously low readings when this type of tailpipe is encountered, the smokemeter should be mounted such that the axis of the smokemeter light beam is perpendicular to and passing through the central axis of the smoke plume (not necessarily the centerline of the pipe) and is parallel to the minor axis of the tailpipe exit. The smokemeter light beam must also be within 70 mm (2.76 in) of the tailpipe exit (Figure D3). If these guidelines are followed, L_m is equal to the tailpipe ID and can usually be adequately approximated by the tailpipe OD (see D.2.2).

Smokemeter orientations in which the smokemeter light beam is not parallel to the minor axis of the tailpipe exit may be used, but in these cases it will be necessary to determine L_m by direct measurement.

D.2.6 **Non-Circular Tailpipe**—If the tailpipe cross section is non-circular, the smokemeter should be mounted such that the smokemeter light beam is perpendicular to and passes through the central axis of the smoke plume and is within 70 mm (2.76 in) of the tailpipe exit. For these cases, L_m will need to be determined by direct measurement. If the tailpipe cross section is an oval or ellipse, it is recommended that the smokemeter light beam be aligned with either the major or minor axis of the tailpipe cross section in order to facilitate the measurement of L_m (Figure D4).

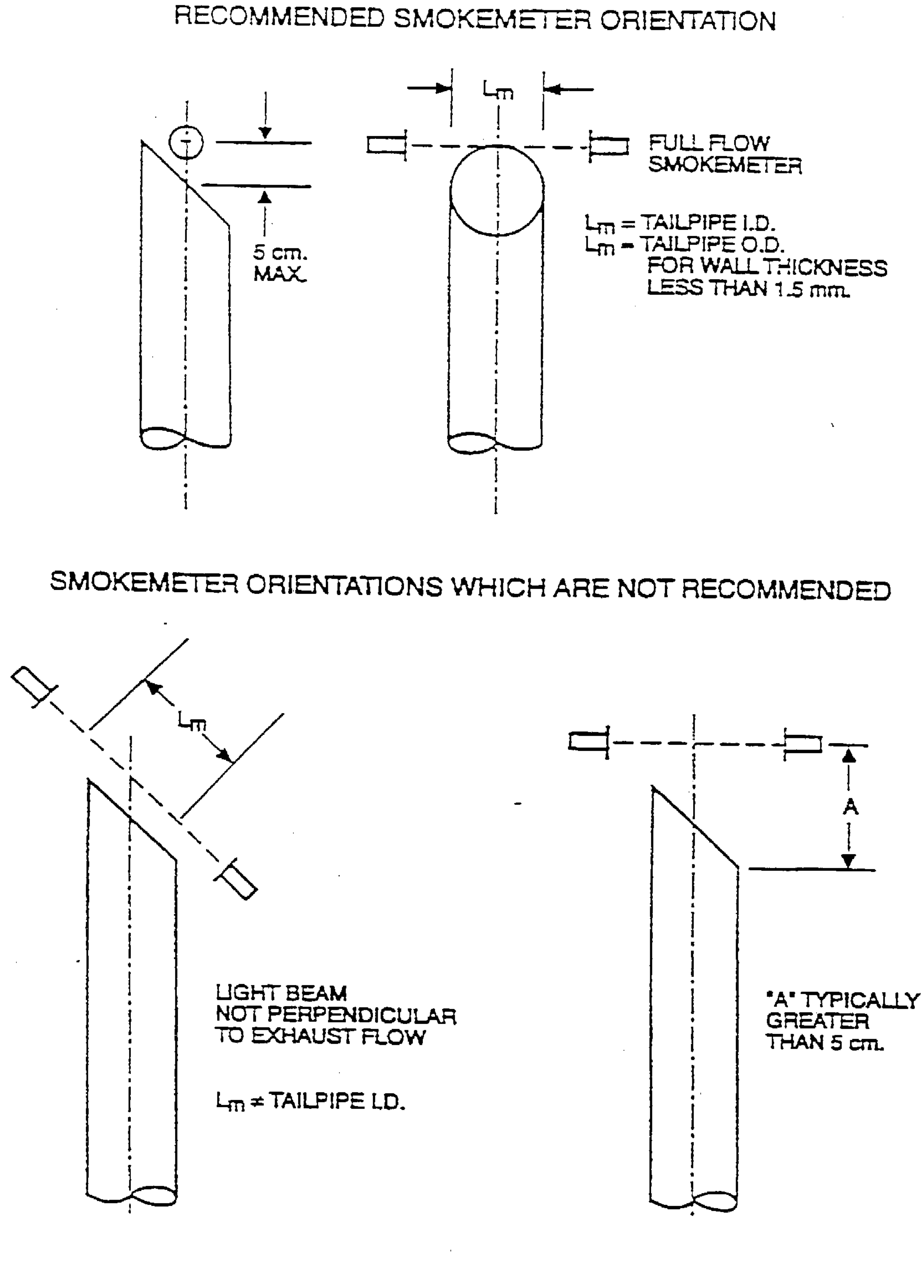
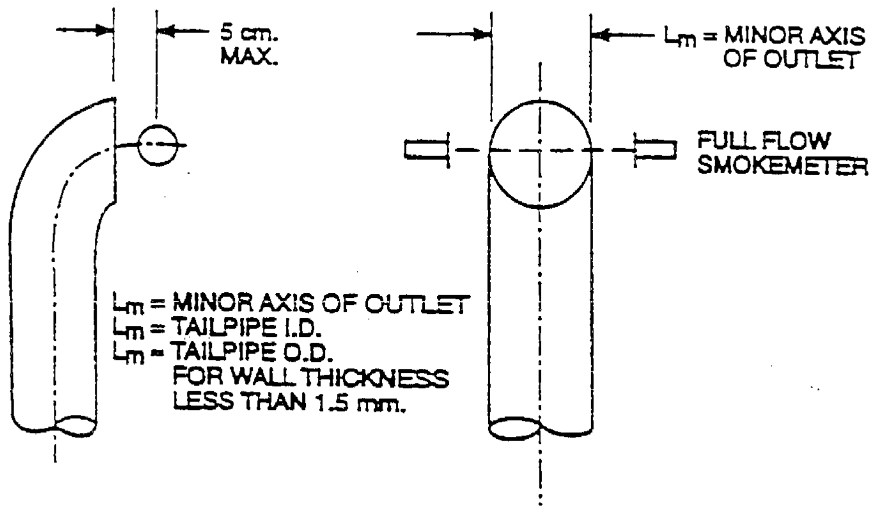


FIGURE D2—STRAIGHT CIRCULAR BEVELED TAILPIPE

RECOMMENDED SMOKEMETER ORIENTATION



ACCEPTABLE SMOKEMETER ORIENTATION

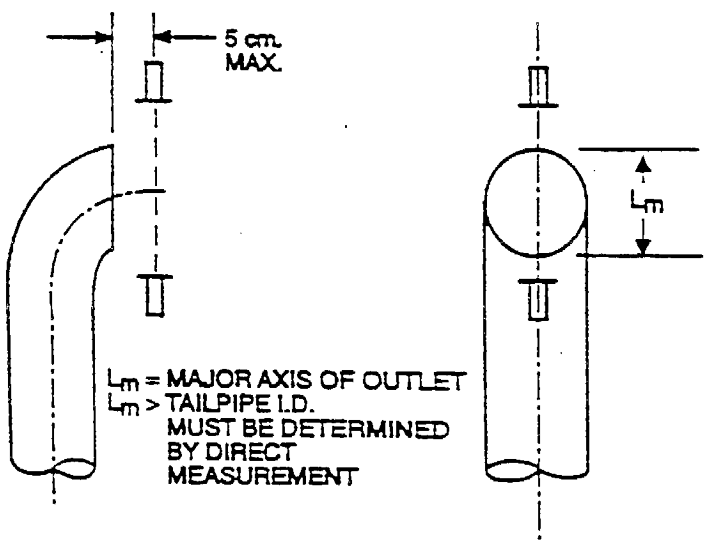


FIGURE D3—CURVED CIRCULAR TAILPIPE

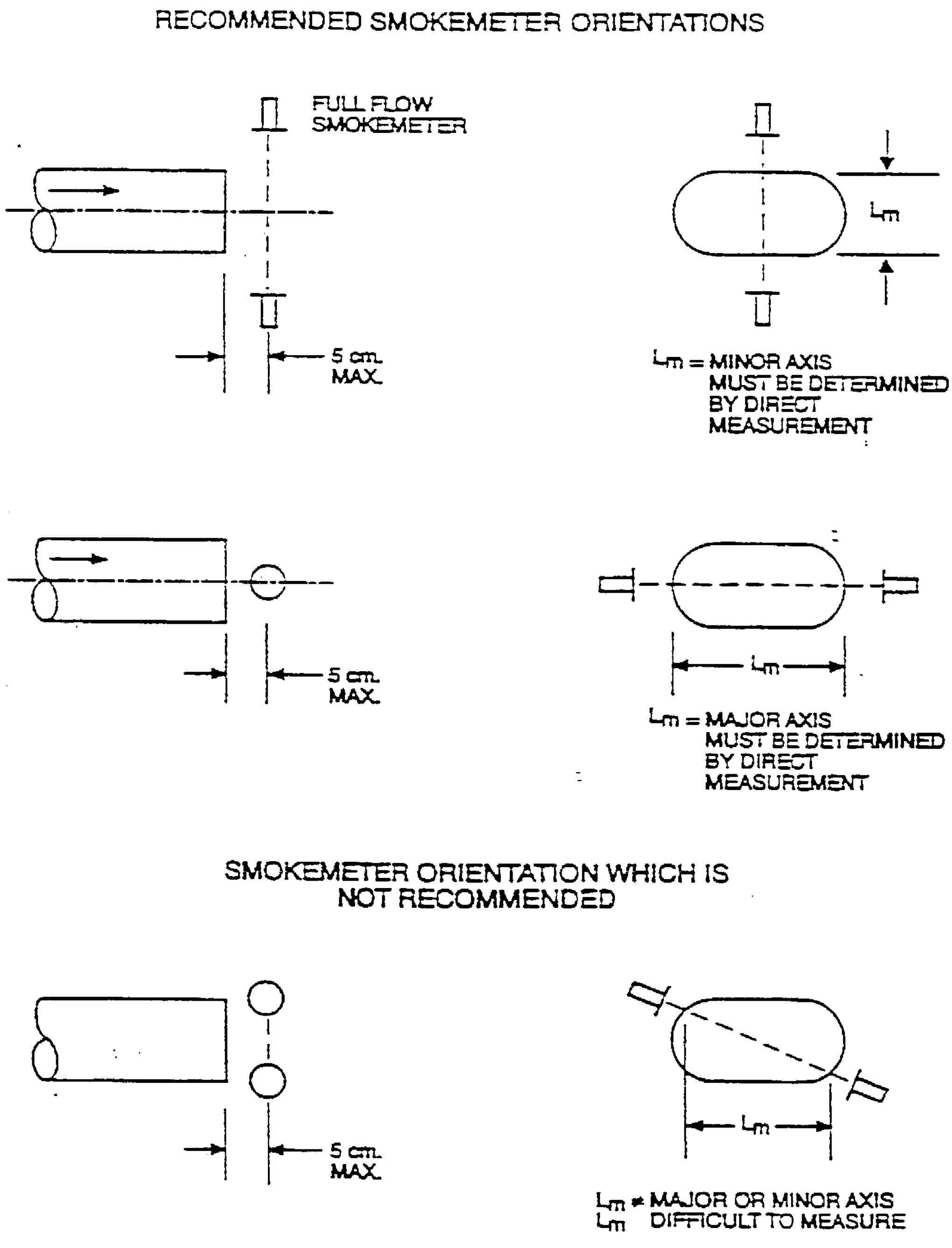


FIGURE D4—NON-CIRCULAR TAILPIPE

D.3 Other Conditions

D.3.1 Rain Caps—Smoke measurements cannot be performed using a full-flow end-of-line smokemeter when a tailpipe rain cap is operational. If present, rain caps must be removed or secured in the fully open position prior to smoke testing. If the smokemeter is installed without removing the rain cap, the meter must be oriented so that the cap does not interfere with the smoke plume or block any portion of the smokemeter light beam (Figure D5).

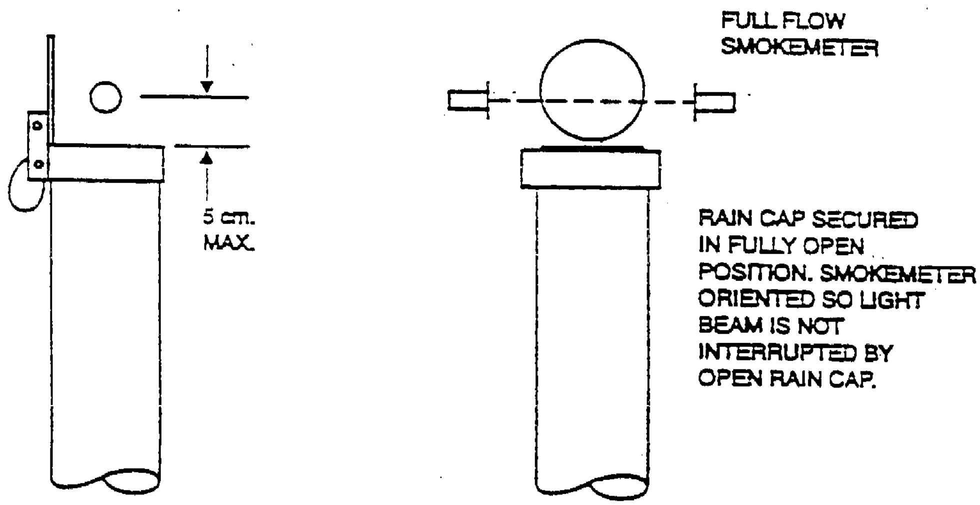


FIGURE D5—RAIN CAP

D.3.2 Downward Directed Exhaust—Many vehicles have horizontal exhaust systems affixed to the underside of the vehicle chassis. Typically these exhaust systems have a curved tailpipe which directs the exhaust flow down against the surface of the roadway.

Care should be exercised when using a full-flow end-of-line smokemeter with vehicles having this type of exhaust system. In some cases, exhaust gases can "rebound" off the roadway surface and recirculate through the smokemeter light beam causing erroneously high smoke measurements. This condition can be aggravated if road dust becomes entrained in the recirculating exhaust flow.

In most cases, little can be done to prevent this condition; however, it is recommended that testing personnel attempt to observe whether recirculation is occurring when testing vehicles with downward directed exhaust systems. If recirculation appears to be influencing the smoke measurement, the test results should be considered unreliable (too high) and should be used with caution.

Rationale—Not applicable.

Relationship of SAE Standard to ISO Standard—Not applicable.

Application—This SAE Recommended Practice applies to vehicle exhaust smoke measurements made using the Snap-Acceleration test procedure. Because this is a non-moving vehicle test, this test can be conducted along the roadside, in a truck depot, a vehicle repair facility, or other test facilities. The test is intended to be used on heavy-duty trucks and buses powered by diesel engines. It is designed to be used in conjunction with smokemeters using the light extinction principle of smoke measurement.

This procedure describes how the snap-acceleration test is to be performed. It also gives specifications for the smokemeter and other test instrumentation and describes the algorithm for the measurement and quantification of the exhaust smoke produced during the test. Included are discussions of factors which influence snap-acceleration test results and methods to correct for these conditions. Unless otherwise noted, these correction methodologies are to be considered an integral part of the snap-acceleration test procedure.

Reference Section

SAE J255a—Diesel Engine Smoke Measurement

SAE J1243—Diesel Emission Production Audit Test Procedure

SAE J1349—Engine Power Test Code—Spark Ignition and Compression Ignition—Net Power Rating

SAE J1995—Engine Power Test Code—Spark Ignition and Compression Ignition—Gross Power Rating

ISO CD 11614—Apparatus for the Measurement of the Opacity of the Light Absorption Coefficient of Exhaust Gas from Internal Combustion Engines

Code of Federal Regulations (CFR), Title 40, Part 86, Subpart I—Emission Regulation for New Diesel Heavy-Duty Engines: Smoke Exhaust Test Procedure

Procedures for Demonstrating Correlation Among Smokemeters

Developed by the SAE Heavy-Duty In-Use Emission Standards Committee

APPENDIX B

Heavy-Duty Diesel Vehicle Inspection/Maintenance Programs in Other States

APPENDIX B

PROGRAMS IN OTHER STATES

A number of states have initiated heavy-duty diesel inspection/maintenance (I/M) programs, of varying degrees of effectiveness. As of mid-1997, three states outside of California, Arizona, Washington and Colorado, have operational I/M programs for heavy-duty diesels that have been in existence for over 1 year. Two other states, Utah and Nevada, have started new programs within the last year, while other states are initiating or conducting pilot programs. A summary of the programs, their test procedures, cutpoints and failure rates is provided below.

Arizona

Arizona has the oldest operating program in the nation, and utilizes the "lug down" test for heavy duty diesel vehicles (defined as those vehicles whose gross vehicle weight is over 26,000 lbs.) The testing is conducted at centralized testing facilities for vehicles registered in the Phoenix and Tucson metropolitan areas. Each heavy-duty diesel vehicle is mounted on a twin-roll dynamometer, and the truck is accelerated to governed speed. Dynamometer load is then progressively increased until engine speed drops to 80 percent of governed speed, at wide-open throttle. Smoke is measured using a light-extinction type smokemeter, with the detection unit mounted on the exhaust stack. Heavy-duty diesel vehicles with a continuous smoke opacity greater than 20 percent in Phoenix area (30 percent in the Tucson area) are considered to fail the test. The failure rate in Phoenix for 1996 was only 3.72 percent with approximately 7,200 vehicles tested.

Colorado

Colorado has had a functioning program since 1990. The current law requires that all heavy-duty trucks greater than 7,500 lb empty weight (usually corresponding to a gross vehicle weight of about 14,000 to 16,000 lb) be subjected to a smoke inspection using one of the following tests:

- An on-road acceleration test;
- A lug down test using the truck's brakes;
- A loaded test at transmission stall speed for automatic transmission vehicles;
- A lug down test using a dynamometer (similar to the procedure used in Arizona) with smoke measurements at full throttle and 100, 90, 80 and 70 percent of rated speed.

Although high-idle and snap-acceleration tests are not required, the tests are often performed for informational purposes, but have no bearing on the pass/fail determination. Tests are conducted under two parallel programs. The first is a self-certification program for fleets with 10 or more vehicles. The second is under a decentralized I/M program for vehicles not in covered fleets. The decentralized program requires the use of the dynamometer based lug-down test. Both programs are applicable only to those vehicles registered in specific counties in Colorado. Colorado has a cutpoint of 35 percent opacity continuous smoke for naturally-aspirated heavy-duty diesel vehicles and 20 percent for turbocharged heavy-duty diesel vehicles. Typical failure rates have been in the 3 to 4 percent range for naturally-aspirated vehicles, and about 1 percent for turbocharged vehicles.

Nevada

Nevada initiated a program effective July 1, 1996, for heavy-duty diesel vehicles. The test used is the snap-acceleration test, with the SAE J1667 procedure. Vehicles are selected at random roadside locations for testing, and both in-state and out-of-state vehicles are subject to inspection. The pass/fail cutpoint is 70 percent opacity, but no citations have been issued to date. The state has two roadside teams and plans to issue citations starting in the fall of 1997.

Utah

Utah has also initiated a program in 1996, but its actual operating status is unclear. The state uses the SAE J1667 procedure and has implemented a cutpoint of 70 percent smoke opacity for all heavy-duty vehicles (defined as vehicles whose gross vehicle weight rating is in excess of 16,000 lbs). However, it is not clear if the program is in its enforcement phase.

Washington State

Washington State requires that all heavy-duty diesel vehicles registered in the Seattle/Tacoma, Spokane and Vancouver metropolitan areas be tested biennially, since 1993. The state uses the snap-acceleration test, but it is not clear what the smoke measurement represents, as the smoke meters are not be built to SAE J1667 specifications. Washington State uses a 60 percent smoke opacity limit for 1974 to 1991 model year vehicles and a 40 percent opacity limit for 1992 and later vehicles. Anecdotal data on failures place the rates at around 15 percent, but this is an average rate for light- and heavy-duty diesel vehicles.

A number of other states are operating pilot programs. These states include Connecticut, Maryland, New Jersey, New York and British Columbia (Canada). In addition, all of the North-Eastern states have initiated or completed some testing programs to simply record opacity values on a sample of trucks. With the exception of New York, these states are generally considering the SAE J1667 procedure for adoption. Illinois is also expected to institute a program but activities are currently on hold.

APPENDIX C

MVEI7G MODELING PARAMETER INPUT FILES

EXHIBIT C1

1999 MVEI7G MODELING PARAMETER INPUT FILE

FILE: HDDVIM.99 (7/25/97, Dan Meszler, EEA)
This file contains the coefficients for calculating the correction factors for heavy-duty trucks due to the Heavy-Duty Vehicle Smoke & Tampering Inspection Program, as well as, the correction factors for heavy-duty trucks and urban busses due to the use of clean diesel fuels.

These input data are derived from HDVIP TSD 1999 Scenario and reflect impacts predicted by modified Radian/EEA malperformance/repair model expressed in a format constrained by the EMFAC7G BER correction algorithm.

***************** The LAST YEAR in column 3 refers to *****************

			------- model years --------- SMOKE ENFORCEMENT	DTEML			---- calendar years ----			model years CLEAN FUELS	
VEH. TYPE	VEH. TECH	LAST YEAR	FR XXX.XX	TOG XXX.XX	NOx XXX.XX	PMEX XXX.XX	AVAL X.XX	BVAL XXX.XX	TARGET XXX.XX	NOx X.XX	PMEX X.XX
LHD	DSL	1965	42.09	46.54	0.19	53.61	0.00	0.00	0.00	0.94	0.80
LHD	DSL	1966	41.90	46.62	0.19	53.66	0.00	0.00	0.00	0.94	0.80
LHD	DSL	1967	41.71	46.71	0.19	53.71	0.00	0.00	0.00	0.94	0.80
LHD	DSL	1968	41.52	46.79	0.19	53.77	0.00	0.00	0.00	0.94	0.80
LHD	DSL	1969	41.32	46.88	0.18	53.82	0.00	0.00	0.00	0.94	0.80
LHD	DSL	1970	41.11	46.98	0.18	53.88	0.00	0.00	0.00	0.94	0.80
LHD	DSL	1971	40.89	47.08	0.18	53.94	0.00	0.00	0.00	0.94	0.80
LHD	DSL	1972	40.67	47.18	0.18	54.01	0.00	0.00	0.00	0.94	0.80
LHD	DSL	1973	40.44	47.29	0.17	54.07	0.00	0.00	0.00	0.94	0.80
LHD	DSL	1974	40.20	47.40	0.17	54.14	0.00	0.00	0.00	0.94	0.80
LHD	DSL	1975	39.95	47.52	0.17	54.22	0.00	0.00	0.00	0.94	0.80
LHD	DSL	1976	39.69	47.65	0.16	54.30	0.00	0.00	0.00	0.94	0.80
LHD	DSL	1977	39.42	47.78	0.16	54.38	0.00	0.00	0.00	0.94	0.80
LHD	DSL	1978	39.14	47.92	0.16	54.47	0.00	0.00	0.00	0.94	0.80
LHD	DSL	1979	38.85	48.07	0.15	54.56	0.00	0.00	0.00	0.94	0.80
LHD	DSL	1980	38.54	48.23	0.15	54.66	0.00	0.00	0.00	0.94	0.80
LHD	DSL	1981	38.21	48.40	0.15	54.77	0.00	0.00	0.00	0.94	0.80
LHD	DSL	1982	37.87	48.58	0.14	54.88	0.00	0.00	0.00	0.94	0.80
LHD	DSL	1983	37.51	48.77	0.14	55.01	0.00	0.00	0.00	0.94	0.80
LHD	DSL	1984	37.12	48.98	0.13	55.14	0.00	0.00	0.00	0.94	0.80
LHD	DSL	1985	36.71	49.20	0.13	55.29	0.00	0.00	0.00	0.94	0.80
LHD	DSL	1986	36.27	49.45	0.12	55.45	0.00	0.00	0.00	0.94	0.80
LHD	DSL	1987	35.80	49.72	0.11	55.62	0.00	0.00	0.00	0.94	0.80
LHD	DSL	1988	35.30	49.97	0.90	55.78	0.00	0.00	0.00	0.94	0.80
LHD	DSL	1989	34.74	50.30	0.90	56.00	0.00	0.00	0.00	0.94	0.80
LHD	DSL	1990	34.14	50.68	0.91	56.25	0.00	0.00	0.00	0.94	0.80
LHD	DSL	1991	34.46	68.31	8.73	83.08	0.00	0.00	0.00	0.87	0.69
LHD	DSL	1992	34.00	68.60	8.83	83.34	0.50	96.50	79.24	0.87	0.69
LHD	DSL	1993	33.53	68.90	8.93	83.61	1.00	96.50	79.24	0.87	0.69
LHD	DSL	1994	33.07	69.99	10.27	102.59	0.50	96.50	79.24	0.87	0.90
LHD	DSL	1995	32.61	70.32	10.38	102.91	0.00	0.00	0.00	0.87	0.90
LHD	DSL	1996	32.15	70.67	10.50	103.23	0.00	0.00	0.00	0.87	0.90
LHD	DSL	1997	31.69	71.02	10.62	103.57	0.00	0.00	0.00	0.87	0.90
LHD	DSL	1998	31.22	71.38	10.74	103.92	0.50	96.50	79.24	0.87	0.90
LHD	DSL	1999	31.22	71.38	10.74	103.92	1.00	96.50	79.24	0.87	0.90

EXHIBIT C1

1999 MVEI7G MODELING PARAMETER INPUT FILE

- Continuation -

LHD	DSL	2000	31.22	71.38	10.74	103.92	1.00	96.50	79.24	0.87	0.90
LHD	DSL	2001	31.22	71.38	10.74	103.92	1.00	96.50	79.24	0.87	0.90
LHD	DSL	2002	31.22	71.38	10.74	103.92	1.00	96.50	79.24	0.87	0.90
LHD	DSL	2003	31.22	71.38	10.74	103.92	1.00	96.50	79.24	0.87	0.90
LHD	DSL	2004	31.22	71.38	10.74	103.92	1.00	96.50	79.24	0.87	0.90
LHD	DSL	2005	31.22	71.38	10.74	103.92	1.00	96.50	79.24	0.87	0.90
LHD	DSL	2006	31.22	71.38	10.74	103.92	1.00	96.50	79.24	0.87	0.90
LHD	DSL	2007	31.22	71.38	10.74	103.92	1.00	96.50	79.24	0.87	0.90
LHD	DSL	2008	31.22	71.38	10.74	103.92	1.00	96.50	79.24	0.87	0.90
LHD	DSL	2009	31.22	71.38	10.74	103.92	1.00	96.50	79.24	0.87	0.90
LHD	DSL	2010	31.22	71.38	10.74	103.92	1.00	96.50	79.24	0.87	0.90
LHD	DSL	2050	31.22	71.38	10.74	103.92	1.00	96.50	79.24	0.87	0.90
MHD	DSL	1965	63.82	53.71	5.78	78.30	0.00	0.00	0.00	0.94	0.80
MHD	DSL	1966	63.26	53.70	5.79	78.12	0.00	0.00	0.00	0.94	0.80
MHD	DSL	1967	62.70	53.68	5.81	77.93	0.00	0.00	0.00	0.94	0.80
MHD	DSL	1968	62.11	53.66	5.83	77.73	0.00	0.00	0.00	0.94	0.80
MHD	DSL	1969	61.51	53.65	5.85	77.54	0.00	0.00	0.00	0.94	0.80
MHD	DSL	1970	60.88	53.63	5.87	77.34	0.00	0.00	0.00	0.94	0.80
MHD	DSL	1971	60.24	53.61	5.89	77.13	0.00	0.00	0.00	0.94	0.80
MHD	DSL	1972	59.57	53.60	5.91	76.92	0.00	0.00	0.00	0.94	0.80
MHD	DSL	1973	58.88	53.58	5.94	76.70	0.00	0.00	0.00	0.94	0.80
MHD	DSL	1974	58.16	53.57	5.96	76.48	0.00	0.00	0.00	0.94	0.80
MHD	DSL	1975	57.41	53.55	5.99	76.25	0.00	0.00	0.00	0.94	0.80
MHD	DSL	1976	56.63	53.53	6.01	76.02	0.00	0.00	0.00	0.94	0.80
MHD	DSL	1977	55.82	53.52	6.04	75.78	0.00	0.00	0.00	0.94	0.80
MHD	DSL	1978	54.98	53.50	6.07	75.53	0.00	0.00	0.00	0.94	0.80
MHD	DSL	1979	54.09	53.49	6.10	75.27	0.00	0.00	0.00	0.94	0.80
MHD	DSL	1980	53.16	53.48	6.13	75.00	0.00	0.00	0.00	0.94	0.80
MHD	DSL	1981	52.19	53.46	6.17	74.73	0.00	0.00	0.00	0.94	0.80
MHD	DSL	1982	51.16	53.45	6.21	74.44	0.00	0.00	0.00	0.94	0.80
MHD	DSL	1983	50.07	53.44	6.25	74.15	0.00	0.00	0.00	0.94	0.80
MHD	DSL	1984	48.92	53.44	6.29	73.84	0.00	0.00	0.00	0.94	0.80
MHD	DSL	1985	47.69	53.43	6.34	73.52	0.00	0.00	0.00	0.94	0.80
MHD	DSL	1986	46.38	53.43	6.39	73.18	0.00	0.00	0.00	0.94	0.80
MHD	DSL	1987	44.97	53.43	6.45	72.83	0.00	0.00	0.00	0.94	0.80
MHD	DSL	1988	43.44	51.19	6.76	67.54	0.00	0.00	0.00	0.94	0.80
MHD	DSL	1989	41.79	51.21	6.83	67.26	0.00	0.00	0.00	0.94	0.80
MHD	DSL	1990	39.97	51.25	6.92	66.95	0.00	0.00	0.00	0.94	0.80
MHD	DSL	1991	40.93	69.18	9.55	88.41	0.00	0.00	0.00	0.87	0.69
MHD	DSL	1992	39.54	69.03	9.65	87.97	0.50	92.07	79.24	0.87	0.69
MHD	DSL	1993	38.15	68.88	9.75	87.54	1.00	92.07	79.24	0.87	0.69
MHD	DSL	1994	36.77	69.46	10.72	106.37	0.50	92.07	79.24	0.87	0.90
MHD	DSL	1995	35.38	69.33	10.84	105.64	0.00	0.00	0.00	0.87	0.90
MHD	DSL	1996	34.00	69.21	10.95	104.94	0.00	0.00	0.00	0.87	0.90
MHD	DSL	1997	32.61	69.09	11.07	104.25	0.00	0.00	0.00	0.87	0.90
MHD	DSL	1998	31.22	68.99	11.19	103.58	0.50	92.07	79.24	0.87	0.90
MHD	DSL	1999	31.22	68.99	11.19	103.58	1.00	92.07	79.24	0.87	0.90
MHD	DSL	2000	31.22	68.99	11.19	103.58	1.00	92.07	79.24	0.87	0.90
MHD	DSL	2001	31.22	68.99	11.19	103.58	1.00	92.07	79.24	0.87	0.90
MHD	DSL	2002	31.22	68.99	11.19	103.58	1.00	92.07	79.24	0.87	0.90
MHD	DSL	2003	31.22	68.99	11.19	103.58	1.00	92.07	79.24	0.87	0.90
MHD	DSL	2004	31.22	68.99	11.19	103.58	1.00	92.07	79.24	0.87	0.90
MHD	DSL	2005	31.22	68.99	11.19	103.58	1.00	92.07	79.24	0.87	0.90
MHD	DSL	2006	31.22	68.99	11.19	103.58	1.00	92.07	79.24	0.87	0.90
MHD	DSL	2007	31.22	68.99	11.19	103.58	1.00	92.07	79.24	0.87	0.90

EXHIBIT C1

1999 MVEI7G MODELING PARAMETER INPUT FILE

- Continuation -

MHD	DSL	2008	31.22	68.99	11.19	103.58	1.00	92.07	79.24	0.87	0.90
MHD	DSL	2009	31.22	68.99	11.19	103.58	1.00	92.07	79.24	0.87	0.90
MHD	DSL	2010	31.22	68.99	11.19	103.58	1.00	92.07	79.24	0.87	0.90
MHD	DSL	2050	31.22	68.99	11.19	103.58	1.00	92.07	79.24	0.87	0.90
HHD	DSL	1965	78.22	50.52	4.89	89.98	0.00	0.00	0.00	0.94	0.80
HHD	DSL	1966	77.42	50.44	4.90	89.52	0.00	0.00	0.00	0.94	0.80
HHD	DSL	1967	76.61	50.37	4.91	89.05	0.00	0.00	0.00	0.94	0.80
HHD	DSL	1968	75.77	50.30	4.92	88.58	0.00	0.00	0.00	0.94	0.80
HHD	DSL	1969	74.90	50.22	4.93	88.09	0.00	0.00	0.00	0.94	0.80
HHD	DSL	1970	74.01	50.14	4.94	87.60	0.00	0.00	0.00	0.94	0.80
HHD	DSL	1971	73.08	50.06	4.95	87.09	0.00	0.00	0.00	0.94	0.80
HHD	DSL	1972	72.12	49.98	4.97	86.58	0.00	0.00	0.00	0.94	0.80
HHD	DSL	1973	71.13	49.89	4.98	86.05	0.00	0.00	0.00	0.94	0.80
HHD	DSL	1974	70.10	49.81	4.99	85.52	0.00	0.00	0.00	0.94	0.80
HHD	DSL	1975	69.03	49.72	5.01	84.97	0.00	0.00	0.00	0.94	0.80
HHD	DSL	1976	67.92	49.63	5.02	84.41	0.00	0.00	0.00	0.94	0.80
HHD	DSL	1977	66.75	49.53	5.03	83.83	0.00	0.00	0.00	0.94	0.80
HHD	DSL	1978	65.54	49.44	5.05	83.24	0.00	0.00	0.00	0.94	0.80
HHD	DSL	1979	64.27	49.34	5.07	82.63	0.00	0.00	0.00	0.94	0.80
HHD	DSL	1980	62.94	49.24	5.09	82.00	0.00	0.00	0.00	0.94	0.80
HHD	DSL	1981	61.54	49.13	5.11	81.35	0.00	0.00	0.00	0.94	0.80
HHD	DSL	1982	60.06	49.02	5.13	80.69	0.00	0.00	0.00	0.94	0.80
HHD	DSL	1983	58.50	48.91	5.15	80.00	0.00	0.00	0.00	0.94	0.80
HHD	DSL	1984	56.85	48.80	5.17	79.28	0.00	0.00	0.00	0.94	0.80
HHD	DSL	1985	55.09	48.67	5.20	78.54	0.00	0.00	0.00	0.94	0.80
HHD	DSL	1986	53.20	48.55	5.23	77.76	0.00	0.00	0.00	0.94	0.80
HHD	DSL	1987	51.18	48.42	5.26	76.95	0.00	0.00	0.00	0.94	0.80
HHD	DSL	1988	48.99	43.65	8.77	69.30	0.00	0.00	0.00	0.94	0.80
HHD	DSL	1989	46.62	43.57	8.85	68.62	0.00	0.00	0.00	0.94	0.80
HHD	DSL	1990	44.02	43.49	8.94	67.89	0.00	0.00	0.00	0.94	0.80
HHD	DSL	1991	40.93	52.17	14.82	76.68	0.00	0.00	0.00	0.87	0.69
HHD	DSL	1992	39.54	52.16	14.96	76.42	0.50	90.25	79.24	0.87	0.69
HHD	DSL	1993	38.15	52.14	15.11	76.16	1.00	90.25	79.24	0.87	0.69
HHD	DSL	1994	36.77	52.55	15.25	91.86	0.50	90.25	79.24	0.87	0.90
HHD	DSL	1995	35.38	52.56	15.40	91.41	0.00	0.00	0.00	0.87	0.90
HHD	DSL	1996	34.00	52.57	15.55	90.98	0.00	0.00	0.00	0.87	0.90
HHD	DSL	1997	32.61	52.58	15.71	90.56	0.00	0.00	0.00	0.87	0.90
HHD	DSL	1998	31.22	52.60	15.87	90.15	0.50	90.25	79.24	0.87	0.90
HHD	DSL	1999	31.22	52.60	15.87	90.15	1.00	90.25	79.24	0.87	0.90
HHD	DSL	2000	31.22	52.60	15.87	90.15	1.00	90.25	79.24	0.87	0.90
HHD	DSL	2001	31.22	52.60	15.87	90.15	1.00	90.25	79.24	0.87	0.90
HHD	DSL	2002	31.22	52.60	15.87	90.15	1.00	90.25	79.24	0.87	0.90
HHD	DSL	2003	31.22	52.60	15.87	90.15	1.00	90.25	79.24	0.87	0.90
HHD	DSL	2004	31.22	52.60	15.87	90.15	1.00	90.25	79.24	0.87	0.90
HHD	DSL	2005	31.22	52.60	15.87	90.15	1.00	90.25	79.24	0.87	0.90
HHD	DSL	2006	31.22	52.60	15.87	90.15	1.00	90.25	79.24	0.87	0.90
HHD	DSL	2007	31.22	52.60	15.87	90.15	1.00	90.25	79.24	0.87	0.90
HHD	DSL	2008	31.22	52.60	15.87	90.15	1.00	90.25	79.24	0.87	0.90
HHD	DSL	2009	31.22	52.60	15.87	90.15	1.00	90.25	79.24	0.87	0.90
HHD	DSL	2010	31.22	52.60	15.87	90.15	1.00	90.25	79.24	0.87	0.90
HHD	DSL	2050	31.22	52.60	15.87	90.15	1.00	90.25	79.24	0.87	0.90
UBD	DSL	1965	78.22	35.48	3.63	51.09	0.00	0.00	0.00	0.94	0.80
UBD	DSL	1966	77.42	35.48	3.64	51.00	0.00	0.00	0.00	0.94	0.80
UBD	DSL	1967	76.61	35.48	3.66	50.92	0.00	0.00	0.00	0.94	0.80
UBD	DSL	1968	75.77	35.48	3.67	50.83	0.00	0.00	0.00	0.94	0.80

EXHIBIT C1

1999 MVEI7G MODELING PARAMETER INPUT FILE

- Continuation -

UBD	DSL	1969	74.90	35.48	3.69	50.74	0.00	0.00	0.00	0.94	0.80
UBD	DSL	1970	74.01	35.49	3.70	50.65	0.00	0.00	0.00	0.94	0.80
UBD	DSL	1971	73.08	35.49	3.72	50.55	0.00	0.00	0.00	0.94	0.80
UBD	DSL	1972	72.12	35.49	3.73	50.46	0.00	0.00	0.00	0.94	0.80
UBD	DSL	1973	71.13	35.49	3.75	50.36	0.00	0.00	0.00	0.94	0.80
UBD	DSL	1974	70.10	35.50	3.77	50.26	0.00	0.00	0.00	0.94	0.80
UBD	DSL	1975	69.03	35.50	3.79	50.15	0.00	0.00	0.00	0.94	0.80
UBD	DSL	1976	67.92	35.51	3.81	50.05	0.00	0.00	0.00	0.94	0.80
UBD	DSL	1977	66.75	35.52	3.83	49.94	0.00	0.00	0.00	0.94	0.80
UBD	DSL	1978	65.54	35.52	3.86	49.83	0.00	0.00	0.00	0.94	0.80
UBD	DSL	1979	64.27	35.53	3.88	49.71	0.00	0.00	0.00	0.94	0.80
UBD	DSL	1980	62.94	35.54	3.90	49.59	0.00	0.00	0.00	0.94	0.80
UBD	DSL	1981	61.54	35.56	3.93	49.46	0.00	0.00	0.00	0.94	0.80
UBD	DSL	1982	60.06	35.57	3.96	49.34	0.00	0.00	0.00	0.94	0.80
UBD	DSL	1983	58.50	35.58	3.99	49.20	0.00	0.00	0.00	0.94	0.80
UBD	DSL	1984	56.85	35.60	4.03	49.06	0.00	0.00	0.00	0.94	0.80
UBD	DSL	1985	55.09	35.62	4.06	48.92	0.00	0.00	0.00	0.94	0.80
UBD	DSL	1986	53.20	35.65	4.10	48.77	0.00	0.00	0.00	0.94	0.80
UBD	DSL	1987	51.18	35.67	4.15	48.61	0.00	0.00	0.00	0.94	0.80
UBD	DSL	1988	48.99	26.89	1.01	34.40	0.00	0.00	0.00	0.94	0.80
UBD	DSL	1989	46.62	26.98	1.02	34.40	0.00	0.00	0.00	0.94	0.80
UBD	DSL	1990	44.02	27.09	1.04	34.41	0.00	0.00	0.00	0.94	0.80
UBD	DSL	1991	40.93	37.24	2.40	66.58	0.00	0.00	0.00	0.87	0.69
UBD	DSL	1992	39.54	37.34	2.43	66.51	0.50	90.25	79.24	0.87	0.69
UBD	DSL	1993	38.15	37.43	2.46	66.44	1.00	90.25	79.24	0.87	0.69
UBD	DSL	1994	36.77	38.59	2.49	66.97	0.50	90.25	79.24	0.87	0.90
UBD	DSL	1995	35.38	38.70	2.52	66.91	0.00	0.00	0.00	0.87	0.90
UBD	DSL	1996	34.00	38.81	2.55	66.86	0.00	0.00	0.00	0.87	0.90
UBD	DSL	1997	32.61	38.93	2.58	66.82	0.00	0.00	0.00	0.87	0.90
UBD	DSL	1998	31.22	39.05	2.61	66.78	0.50	90.25	79.24	0.87	0.90
UBD	DSL	1999	31.22	39.05	2.61	66.78	1.00	90.25	79.24	0.87	0.90
UBD	DSL	2000	31.22	39.05	2.61	66.78	1.00	90.25	79.24	0.87	0.90
UBD	DSL	2001	31.22	39.05	2.61	66.78	1.00	90.25	79.24	0.87	0.90
UBD	DSL	2002	31.22	39.05	2.61	66.78	1.00	90.25	79.24	0.87	0.90
UBD	DSL	2003	31.22	39.05	2.61	66.78	1.00	90.25	79.24	0.87	0.90
UBD	DSL	2004	31.22	39.05	2.61	66.78	1.00	90.25	79.24	0.87	0.90
UBD	DSL	2005	31.22	39.05	2.61	66.78	1.00	90.25	79.24	0.87	0.90
UBD	DSL	2006	31.22	39.05	2.61	66.78	1.00	90.25	79.24	0.87	0.90
UBD	DSL	2007	31.22	39.05	2.61	66.78	1.00	90.25	79.24	0.87	0.90
UBD	DSL	2008	31.22	39.05	2.61	66.78	1.00	90.25	79.24	0.87	0.90
UBD	DSL	2009	31.22	39.05	2.61	66.78	1.00	90.25	79.24	0.87	0.90
UBD	DSL	2010	31.22	39.05	2.61	66.78	1.00	90.25	79.24	0.87	0.90

EXHIBIT C2

2010 MVEI7G MODELING PARAMETER INPUT FILE

FILE: HDDVIM.10 (7/25/97, Dan Meszler, EEA)
This file contains the coefficients for calculating the correction factors for heavy-duty trucks due to the Heavy-Duty Vehicle Smoke & Tampering Inspection Program, as well as, the correction factors for heavy-duty trucks and urban busses due to the use of clean diesel fuels.

These input data are derived from HDVIP TSD 2010 Scenario and reflect impacts predicted by modified Radian/EEA malperformance/repair model expressed in a format constrained by the EMFAC7G BER correction algorithm.

**************** The LAST YEAR in column 3 refers to ****************

			-------- model years ---------	---- calendar years ----						model years	
			SMOKE ENFORCEMENT							CLEAN FUELS	
				DTEML							
VEH. TYPE	VEH. TECH	LAST YEAR	FR XXX.XX	TOG XXX.XX	NOx XXX.XX	PMEX XXX.XX	AVAL X.XX	BVAL XXX.XX	TARGET XXX.XX	NOx X.XX	PMEX X.XX
LHD	DSL	1965	45.11	46.64	0.20	54.02	0.00	0.00	0.00	0.94	0.80
LHD	DSL	1966	44.97	46.70	0.20	54.05	0.00	0.00	0.00	0.94	0.80
LHD	DSL	1967	44.83	46.75	0.20	54.08	0.00	0.00	0.00	0.94	0.80
LHD	DSL	1968	44.69	46.81	0.20	54.12	0.00	0.00	0.00	0.94	0.80
LHD	DSL	1969	44.55	46.87	0.20	54.15	0.00	0.00	0.00	0.94	0.80
LHD	DSL	1970	44.40	46.93	0.19	54.19	0.00	0.00	0.00	0.94	0.80
LHD	DSL	1971	44.24	46.99	0.19	54.22	0.00	0.00	0.00	0.94	0.80
LHD	DSL	1972	44.09	47.06	0.19	54.26	0.00	0.00	0.00	0.94	0.80
LHD	DSL	1973	43.93	47.13	0.19	54.30	0.00	0.00	0.00	0.94	0.80
LHD	DSL	1974	43.76	47.20	0.19	54.34	0.00	0.00	0.00	0.94	0.80
LHD	DSL	1975	43.59	47.27	0.19	54.39	0.00	0.00	0.00	0.94	0.80
LHD	DSL	1976	43.42	47.34	0.18	54.43	0.00	0.00	0.00	0.94	0.80
LHD	DSL	1977	43.24	47.42	0.18	54.48	0.00	0.00	0.00	0.94	0.80
LHD	DSL	1978	43.05	47.50	0.18	54.53	0.00	0.00	0.00	0.94	0.80
LHD	DSL	1979	42.86	47.59	0.18	54.58	0.00	0.00	0.00	0.94	0.80
LHD	DSL	1980	42.66	47.67	0.18	54.63	0.00	0.00	0.00	0.94	0.80
LHD	DSL	1981	42.46	47.76	0.17	54.68	0.00	0.00	0.00	0.94	0.80
LHD	DSL	1982	42.25	47.86	0.17	54.74	0.00	0.00	0.00	0.94	0.80
LHD	DSL	1983	42.03	47.96	0.17	54.80	0.00	0.00	0.00	0.94	0.80
LHD	DSL	1984	41.81	48.06	0.17	54.86	0.00	0.00	0.00	0.94	0.80
LHD	DSL	1985	41.57	48.17	0.16	54.93	0.00	0.00	0.00	0.94	0.80
LHD	DSL	1986	41.33	48.28	0.16	55.00	0.00	0.00	0.00	0.94	0.80
LHD	DSL	1987	41.08	48.40	0.16	55.07	0.00	0.00	0.00	0.94	0.80
LHD	DSL	1988	40.81	48.46	0.88	55.08	0.00	0.00	0.00	0.94	0.80
LHD	DSL	1989	40.54	48.60	0.88	55.17	0.00	0.00	0.00	0.94	0.80
LHD	DSL	1990	40.25	48.74	0.88	55.26	0.00	0.00	0.00	0.94	0.80
LHD	DSL	1991	40.93	66.69	7.92	82.25	0.00	0.00	0.00	0.87	0.69
LHD	DSL	1992	40.47	66.90	7.99	82.42	0.50	96.61	79.75	0.87	0.69
LHD	DSL	1993	40.02	67.11	8.06	82.59	1.00	96.61	79.75	0.87	0.69
LHD	DSL	1994	39.57	67.94	9.26	101.92	0.50	96.61	79.75	0.87	0.90
LHD	DSL	1995	39.12	68.18	9.35	102.11	0.00	0.00	0.00	0.87	0.90
LHD	DSL	1996	38.67	68.42	9.44	102.31	0.00	0.00	0.00	0.87	0.90
LHD	DSL	1997	38.22	68.67	9.53	102.52	0.00	0.00	0.00	0.87	0.90
LHD	DSL	1998	37.77	68.93	9.62	102.74	0.50	96.61	79.75	0.87	0.90
LHD	DSL	1999	37.31	69.19	9.71	102.96	1.00	96.61	79.75	0.87	0.90

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LHD	DSL	2000	36.86	69.46	9.81	103.19	1.00	96.61	79.75	0.87	0.90
LHD	DSL	2001	36.41	69.74	9.91	103.43	1.00	96.61	79.75	0.87	0.90
LHD	DSL	2002	35.96	70.02	10.01	103.68	1.00	96.61	79.75	0.87	0.90
LHD	DSL	2003	35.51	70.31	10.11	103.93	1.00	96.61	79.75	0.87	0.90
LHD	DSL	2004	35.06	70.61	10.21	104.19	1.00	96.61	79.75	0.87	0.90
LHD	DSL	2005	34.61	70.91	10.32	104.47	1.00	96.61	79.75	0.87	0.90
LHD	DSL	2006	34.15	71.22	10.42	104.75	1.00	96.61	79.75	0.87	0.90
LHD	DSL	2007	33.70	71.54	10.53	105.04	1.00	96.61	79.75	0.87	0.90
LHD	DSL	2008	33.25	71.86	10.65	105.34	1.00	96.61	79.75	0.87	0.90
LHD	DSL	2009	32.80	72.19	10.76	105.65	1.00	96.61	79.75	0.87	0.90
LHD	DSL	2010	32.80	72.19	10.76	105.65	1.00	96.61	79.75	0.87	0.90
LHD	DSL	2050	32.80	72.19	10.76	105.65	1.00	96.61	79.75	0.87	0.90
MHD	DSL	1965	69.73	54.79	5.71	81.34	0.00	0.00	0.00	0.94	0.80
MHD	DSL	1966	69.32	54.77	5.72	81.18	0.00	0.00	0.00	0.94	0.80
MHD	DSL	1967	68.90	54.75	5.73	81.02	0.00	0.00	0.00	0.94	0.80
MHD	DSL	1968	68.47	54.73	5.74	80.86	0.00	0.00	0.00	0.94	0.80
MHD	DSL	1969	68.04	54.71	5.76	80.70	0.00	0.00	0.00	0.94	0.80
MHD	DSL	1970	67.59	54.69	5.77	80.53	0.00	0.00	0.00	0.94	0.80
MHD	DSL	1971	67.13	54.66	5.78	80.36	0.00	0.00	0.00	0.94	0.80
MHD	DSL	1972	66.66	54.64	5.80	80.19	0.00	0.00	0.00	0.94	0.80
MHD	DSL	1973	66.17	54.62	5.81	80.01	0.00	0.00	0.00	0.94	0.80
MHD	DSL	1974	65.68	54.60	5.83	79.83	0.00	0.00	0.00	0.94	0.80
MHD	DSL	1975	65.17	54.58	5.84	79.65	0.00	0.00	0.00	0.94	0.80
MHD	DSL	1976	64.64	54.56	5.86	79.46	0.00	0.00	0.00	0.94	0.80
MHD	DSL	1977	64.11	54.54	5.88	79.27	0.00	0.00	0.00	0.94	0.80
MHD	DSL	1978	63.55	54.51	5.89	79.08	0.00	0.00	0.00	0.94	0.80
MHD	DSL	1979	62.98	54.49	5.91	78.88	0.00	0.00	0.00	0.94	0.80
MHD	DSL	1980	62.39	54.47	5.93	78.68	0.00	0.00	0.00	0.94	0.80
MHD	DSL	1981	61.78	54.45	5.95	78.47	0.00	0.00	0.00	0.94	0.80
MHD	DSL	1982	61.15	54.42	5.97	78.26	0.00	0.00	0.00	0.94	0.80
MHD	DSL	1983	60.50	54.40	5.99	78.04	0.00	0.00	0.00	0.94	0.80
MHD	DSL	1984	59.82	54.38	6.01	77.81	0.00	0.00	0.00	0.94	0.80
MHD	DSL	1985	59.12	54.35	6.03	77.58	0.00	0.00	0.00	0.94	0.80
MHD	DSL	1986	58.39	54.33	6.06	77.35	0.00	0.00	0.00	0.94	0.80
MHD	DSL	1987	57.63	54.31	6.08	77.10	0.00	0.00	0.00	0.94	0.80
MHD	DSL	1988	56.84	51.84	6.32	70.95	0.00	0.00	0.00	0.94	0.80
MHD	DSL	1989	56.01	51.83	6.35	70.76	0.00	0.00	0.00	0.94	0.80
MHD	DSL	1990	55.15	51.82	6.38	70.56	0.00	0.00	0.00	0.94	0.80
MHD	DSL	1991	57.18	72.42	8.69	95.82	0.00	0.00	0.00	0.87	0.69
MHD	DSL	1992	55.82	72.18	8.77	95.21	0.50	92.26	79.75	0.87	0.69
MHD	DSL	1993	54.47	71.95	8.85	94.61	1.00	92.26	79.75	0.87	0.69
MHD	DSL	1994	53.11	72.35	9.73	118.16	0.50	92.26	79.75	0.87	0.90
MHD	DSL	1995	51.76	72.14	9.82	117.14	0.00	0.00	0.00	0.87	0.90
MHD	DSL	1996	50.41	71.93	9.91	116.15	0.00	0.00	0.00	0.87	0.90
MHD	DSL	1997	49.05	71.73	10.00	115.18	0.00	0.00	0.00	0.87	0.90
MHD	DSL	1998	47.70	71.53	10.09	114.24	0.50	92.26	79.75	0.87	0.90
MHD	DSL	1999	46.34	71.34	10.18	113.33	1.00	92.26	79.75	0.87	0.90
MHD	DSL	2000	44.99	71.16	10.28	112.43	1.00	92.26	79.75	0.87	0.90
MHD	DSL	2001	43.63	70.98	10.37	111.56	1.00	92.26	79.75	0.87	0.90
MHD	DSL	2002	42.28	70.81	10.47	110.71	1.00	92.26	79.75	0.87	0.90
MHD	DSL	2003	40.93	70.64	10.57	109.87	1.00	92.26	79.75	0.87	0.90
MHD	DSL	2004	39.57	70.48	10.67	109.06	1.00	92.26	79.75	0.87	0.90
MHD	DSL	2005	38.22	70.32	10.78	108.27	1.00	92.26	79.75	0.87	0.90
MHD	DSL	2006	36.86	70.17	10.88	107.50	1.00	92.26	79.75	0.87	0.90
MHD	DSL	2007	35.51	70.02	10.99	106.75	1.00	92.26	79.75	0.87	0.90

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MHD	DSL	2008	34.15	69.88	11.10	106.02	1.00	92.26	79.75	0.87	0.90
MHD	DSL	2009	32.80	69.74	11.21	105.30	1.00	92.26	79.75	0.87	0.90
MHD	DSL	2010	32.80	69.74	11.21	105.30	1.00	92.26	79.75	0.87	0.90
MHD	DSL	2050	32.80	69.74	11.21	105.30	1.00	92.26	79.75	0.87	0.90
HHD	DSL	1965	86.01	51.95	4.86	95.82	0.00	0.00	0.00	0.94	0.80
HHD	DSL	1966	85.42	51.89	4.86	95.43	0.00	0.00	0.00	0.94	0.80
HHD	DSL	1967	84.82	51.82	4.87	95.02	0.00	0.00	0.00	0.94	0.80
HHD	DSL	1968	84.21	51.76	4.88	94.62	0.00	0.00	0.00	0.94	0.80
HHD	DSL	1969	83.58	51.69	4.89	94.20	0.00	0.00	0.00	0.94	0.80
HHD	DSL	1970	82.94	51.62	4.89	93.79	0.00	0.00	0.00	0.94	0.80
HHD	DSL	1971	82.28	51.55	4.90	93.36	0.00	0.00	0.00	0.94	0.80
HHD	DSL	1972	81.60	51.48	4.91	92.93	0.00	0.00	0.00	0.94	0.80
HHD	DSL	1973	80.91	51.41	4.91	92.49	0.00	0.00	0.00	0.94	0.80
HHD	DSL	1974	80.20	51.34	4.92	92.05	0.00	0.00	0.00	0.94	0.80
HHD	DSL	1975	79.47	51.27	4.93	91.60	0.00	0.00	0.00	0.94	0.80
HHD	DSL	1976	78.72	51.19	4.94	91.14	0.00	0.00	0.00	0.94	0.80
HHD	DSL	1977	77.94	51.11	4.95	90.68	0.00	0.00	0.00	0.94	0.80
HHD	DSL	1978	77.15	51.04	4.96	90.20	0.00	0.00	0.00	0.94	0.80
HHD	DSL	1979	76.33	50.96	4.97	89.72	0.00	0.00	0.00	0.94	0.80
HHD	DSL	1980	75.48	50.87	4.98	89.23	0.00	0.00	0.00	0.94	0.80
HHD	DSL	1981	74.60	50.79	4.99	88.73	0.00	0.00	0.00	0.94	0.80
HHD	DSL	1982	73.70	50.70	5.00	88.22	0.00	0.00	0.00	0.94	0.80
HHD	DSL	1983	72.76	50.62	5.01	87.69	0.00	0.00	0.00	0.94	0.80
HHD	DSL	1984	71.79	50.53	5.02	87.16	0.00	0.00	0.00	0.94	0.80
HHD	DSL	1985	70.79	50.43	5.03	86.62	0.00	0.00	0.00	0.94	0.80
HHD	DSL	1986	69.74	50.34	5.05	86.06	0.00	0.00	0.00	0.94	0.80
HHD	DSL	1987	68.65	50.24	5.06	85.49	0.00	0.00	0.00	0.94	0.80
HHD	DSL	1988	67.52	44.93	8.32	76.07	0.00	0.00	0.00	0.94	0.80
HHD	DSL	1989	66.33	44.87	8.36	75.62	0.00	0.00	0.00	0.94	0.80
HHD	DSL	1990	65.09	44.80	8.39	75.16	0.00	0.00	0.00	0.94	0.80
HHD	DSL	1991	57.18	53.32	13.63	81.43	0.00	0.00	0.00	0.87	0.69
HHD	DSL	1992	55.82	53.25	13.74	81.06	0.50	90.99	79.75	0.87	0.69
HHD	DSL	1993	54.47	53.18	13.85	80.70	1.00	90.99	79.75	0.87	0.69
HHD	DSL	1994	53.11	53.41	13.96	99.43	0.50	90.99	79.75	0.87	0.90
HHD	DSL	1995	51.76	53.36	14.08	98.80	0.00	0.00	0.00	0.87	0.90
HHD	DSL	1996	50.41	53.32	14.19	98.19	0.00	0.00	0.00	0.87	0.90
HHD	DSL	1997	49.05	53.28	14.31	97.60	0.00	0.00	0.00	0.87	0.90
HHD	DSL	1998	47.70	53.24	14.43	97.02	0.50	90.99	79.75	0.87	0.90
HHD	DSL	1999	46.34	53.21	14.56	96.45	1.00	90.99	79.75	0.87	0.90
HHD	DSL	2000	44.99	53.18	14.68	95.89	1.00	90.99	79.75	0.87	0.90
HHD	DSL	2001	43.63	53.15	14.81	95.35	1.00	90.99	79.75	0.87	0.90
HHD	DSL	2002	42.28	53.12	14.94	94.82	1.00	90.99	79.75	0.87	0.90
HHD	DSL	2003	40.93	53.10	15.07	94.30	1.00	90.99	79.75	0.87	0.90
HHD	DSL	2004	39.57	53.08	15.20	93.80	1.00	90.99	79.75	0.87	0.90
HHD	DSL	2005	38.22	53.07	15.34	93.31	1.00	90.99	79.75	0.87	0.90
HHD	DSL	2006	36.86	53.06	15.48	92.83	1.00	90.99	79.75	0.87	0.90
HHD	DSL	2007	35.51	53.05	15.62	92.36	1.00	90.99	79.75	0.87	0.90
HHD	DSL	2008	34.15	53.04	15.76	91.90	1.00	90.99	79.75	0.87	0.90
HHD	DSL	2009	32.80	53.04	15.91	91.45	1.00	90.99	79.75	0.87	0.90
HHD	DSL	2010	32.80	53.04	15.91	91.45	1.00	90.99	79.75	0.87	0.90
HHD	DSL	2050	32.80	53.04	15.91	91.45	1.00	90.99	79.75	0.87	0.90
UBD	DSL	1965	86.01	36.00	3.57	52.60	0.00	0.00	0.00	0.94	0.80
UBD	DSL	1966	85.42	36.00	3.58	52.53	0.00	0.00	0.00	0.94	0.80
UBD	DSL	1967	84.82	36.00	3.59	52.46	0.00	0.00	0.00	0.94	0.80
UBD	DSL	1968	84.21	35.99	3.60	52.38	0.00	0.00	0.00	0.94	0.80

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UBD	DSL	1969	83.58	35.99	3.61	52.31	0.00	0.00	0.00	0.94	0.80
UBD	DSL	1970	82.94	35.98	3.62	52.23	0.00	0.00	0.00	0.94	0.80
UBD	DSL	1971	82.28	35.98	3.63	52.15	0.00	0.00	0.00	0.94	0.80
UBD	DSL	1972	81.60	35.98	3.64	52.07	0.00	0.00	0.00	0.94	0.80
UBD	DSL	1973	80.91	35.97	3.65	51.99	0.00	0.00	0.00	0.94	0.80
UBD	DSL	1974	80.20	35.97	3.67	51.91	0.00	0.00	0.00	0.94	0.80
UBD	DSL	1975	79.47	35.97	3.68	51.82	0.00	0.00	0.00	0.94	0.80
UBD	DSL	1976	78.72	35.96	3.69	51.73	0.00	0.00	0.00	0.94	0.80
UBD	DSL	1977	77.94	35.96	3.70	51.65	0.00	0.00	0.00	0.94	0.80
UBD	DSL	1978	77.15	35.96	3.72	51.56	0.00	0.00	0.00	0.94	0.80
UBD	DSL	1979	76.33	35.96	3.73	51.46	0.00	0.00	0.00	0.94	0.80
UBD	DSL	1980	75.48	35.95	3.74	51.37	0.00	0.00	0.00	0.94	0.80
UBD	DSL	1981	74.60	35.95	3.76	51.27	0.00	0.00	0.00	0.94	0.80
UBD	DSL	1982	73.70	35.95	3.77	51.17	0.00	0.00	0.00	0.94	0.80
UBD	DSL	1983	72.76	35.95	3.79	51.07	0.00	0.00	0.00	0.94	0.80
UBD	DSL	1984	71.79	35.95	3.81	50.97	0.00	0.00	0.00	0.94	0.80
UBD	DSL	1985	70.79	35.95	3.83	50.86	0.00	0.00	0.00	0.94	0.80
UBD	DSL	1986	69.74	35.95	3.84	50.75	0.00	0.00	0.00	0.94	0.80
UBD	DSL	1987	68.65	35.95	3.86	50.64	0.00	0.00	0.00	0.94	0.80
UBD	DSL	1988	67.52	26.58	0.90	34.82	0.00	0.00	0.00	0.94	0.80
UBD	DSL	1989	66.33	26.62	0.91	34.81	0.00	0.00	0.00	0.94	0.80
UBD	DSL	1990	65.09	26.65	0.92	34.79	0.00	0.00	0.00	0.94	0.80
UBD	DSL	1991	57.18	36.83	2.16	68.78	0.00	0.00	0.00	0.87	0.69
UBD	DSL	1992	55.82	36.89	2.18	68.64	0.50	90.99	79.75	0.87	0.69
UBD	DSL	1993	54.47	36.95	2.20	68.50	1.00	90.99	79.75	0.87	0.69
UBD	DSL	1994	53.11	38.04	2.22	68.97	0.50	90.99	79.75	0.87	0.90
UBD	DSL	1995	51.76	38.11	2.24	68.84	0.00	0.00	0.00	0.87	0.90
UBD	DSL	1996	50.41	38.18	2.27	68.71	0.00	0.00	0.00	0.87	0.90
UBD	DSL	1997	49.05	38.25	2.29	68.59	0.00	0.00	0.00	0.87	0.90
UBD	DSL	1998	47.70	38.32	2.31	68.47	0.50	90.99	79.75	0.87	0.90
UBD	DSL	1999	46.34	38.40	2.34	68.36	1.00	90.99	79.75	0.87	0.90
UBD	DSL	2000	44.99	38.47	2.36	68.25	1.00	90.99	79.75	0.87	0.90
UBD	DSL	2001	43.63	38.55	2.39	68.15	1.00	90.99	79.75	0.87	0.90
UBD	DSL	2002	42.28	38.64	2.42	68.05	1.00	90.99	79.75	0.87	0.90
UBD	DSL	2003	40.93	38.72	2.44	67.96	1.00	90.99	79.75	0.87	0.90
UBD	DSL	2004	39.57	38.81	2.47	67.87	1.00	90.99	79.75	0.87	0.90
UBD	DSL	2005	38.22	38.90	2.50	67.79	1.00	90.99	79.75	0.87	0.90
UBD	DSL	2006	36.86	38.99	2.52	67.71	1.00	90.99	79.75	0.87	0.90
UBD	DSL	2007	35.51	39.09	2.55	67.63	1.00	90.99	79.75	0.87	0.90
UBD	DSL	2008	34.15	39.19	2.58	67.56	1.00	90.99	79.75	0.87	0.90
UBD	DSL	2009	32.80	39.29	2.61	67.49	1.00	90.99	79.75	0.87	0.90
UBD	DSL	2010	32.80	39.29	2.61	67.49	1.00	90.99	79.75	0.87	0.90