EFFECT OF MAINTENANCE PRACTICES
AND FUEL QUALITY
ON TRANSIT BUS SMOKE
AND PARTICULATE EMISSIONS

prepared for:

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and
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ABSTRACT

An analysis of smoke emissions from Diesel transit buses indicates that while most buses have peak smoke levels which are invisible or just barely visible, some buses emit peak smoke levels of 40-45% opacity. Buses with the lowest smoke levels tend to be equipped with older, naturally aspirated engines. Buses with the highest smoke levels are usually equipped with later model, turbocharged engines. However, some of these late model engines exhibit very low smoke levels, while others have relatively high smoke levels.

Transit district officials believe that late model, turbocharged engines are more difficult to keep in proper tune. In addition, the <u>variability</u> in smoke emissions from late model turbocharged engines seems to indicate that late model engines are quite sensitive to the manner in which they are maintained. The incorporation of routine smoke measurements may be effective in detecting those engines which are in need of further adjustment.

Analysis of bus engine maintenance histories indicates that the <u>frequency</u> of smoke related maintenance is a very poor predictor of exhaust opacity in customer service. This fact supports the position that bus smoke would be controlled more effectively through an "inspection and maintenance" (I/M) approach, rather than a "mandatory maintenance" approach. Identification and correction of the highest smoke buses of each engine type could reduce smoke and particulate emissions from the entire fleet by approximately 35%.

The use of turbocharging and engine calibrations used to meet current NOx emission standards appears to be related to increased smoke levels; however, the newest turbocharged engines have significantly lower smoke levels than 1980-1982 models. Improved turbocharger matching and other improvements incorporated into new engines may offer some potential for improving the performance of earlier model engines. Because the components used on late model engines are interchangeable with those used on earlier models, the "upgrading" or retrofit of engines during rebuilding may be an effective means of reducing smoke and particulate emissions.

Differences in the engine models used by transit districts made it impossible to determine whether differences in fuel specifications are having a significant effect on smoke emissions from buses. However, a literature review indicates that fuels with lower aromatics content and lower 90% boiling point reduce smoke and particulate emissions. Although the cost of requiring all Diesel fuel to meet more stringent fuel quality specifications may be relatively high, costs would be significantly lower if only the limited amount of Diesel fuel used by transit districts were subject to more stringent requirements.

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DISCLAIMER

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Section 1

SUMMARY AND CONCLUSIONS

Federal emission standards for heavy duty Diesel engines require a certain degree of smoke emissions control; however, engines meeting the federal standards may still exhibit visible smoke, and may emit significant amounts of particulate. The federal smoke standards in force today have been unchanged for eleven years and no smoke or particulate emission standards for heavy-duty Diesels have ever been adopted by the California Air Resources Board.

Recent studies have shown that particulate emissions from heavy-duty Diesel engines contribute significantly to visibility degradation in California. In addition, the effects of Diesel particulate emissions on human health is a serious concern.

Although small in number relative to the total population of vehicles powered by heavy-duty Diesel engines, transit buses are operated almost exclusively in urban areas where the impact of smoke and particulate emissions are of the greatest concern. In addition, smoke and particulate emissions from transit buses have long been considered a nuisance by the general public.

The California Air Resources Board (ARB) has several on-going projects under which the feasibility of further particulate emissions control from Diesel powered vehicles is being investigated. To supplement the existing program, ARB and the South Coast Air Quality Management District (SCAQMD) contracted for a study of the effect of maintenance practices and fuel specifications on smoke emissions from transit buses.

Tasks performed during the course of the study included:

1. A literature review of the effect of maintenance practices and fuel specifications on smoke and particulate emissions;

2. Discussions with maintenance supervisors from three transit districts;

3. Discussions regarding the effect of fuel specifications and maintenance practices with the principal bus engine manufacturer in the U.S.;

4. Documentation of the smoke emissions from hundreds of transit buses in field service using video tape, still photography, and a trained observer;

5. Review of detailed maintenance records and fuel specifications for the buses that were observed in field service;

6. Analysis of maintenance records and fuel specifications in conjunction with smoke emissions data to determine whether correlations were evident;

7. Estimation of the cost of various changes in maintenance practices and fuel specifications; and

8. Preparation of a report summarizing the work performed and drawing conclusions regarding the feasibility and cost-effectiveness of reducing emissions through changes in maintenance practices and fuel specifications.

Field Observations

Bus Smoke Levels Are Highly Variable - The field observations performed during the course of the study indicate that the "average" transit bus has peak smoke emissions of only 7%. At this opacity level, the exhaust plume is only slightly visible and it would not be considered objectionable to the average observer. However, some transit buses have peak opacity levels of 45%. This opacity level is very objectionable to the average observer. Figure 1 shows what an exhaust plume of 30-40% opacity looks like.

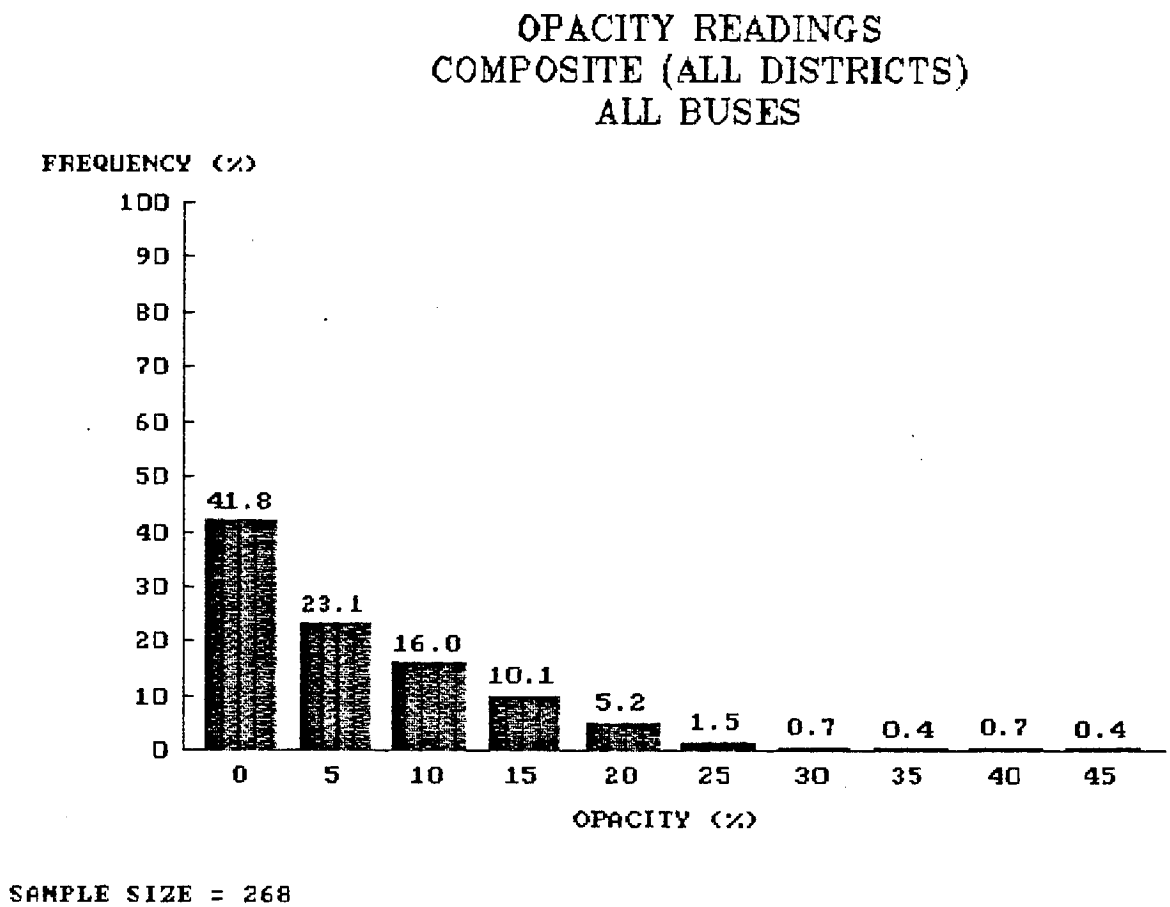
Current laws and regulations governing the opacity of smoke emissions usually use 20% opacity (Ringelmann 1) as the criteria for determining whether the emissions are excessive or not. However, based on the subjective judgment of the personnel involved in the field observations, 20% opacity would probably be considered objectionable to the average person. An opacity level of 10% is considered a better dividing line between buses which are "clean" and buses which are "dirty". The field observations indicated that 35% of transit buses have peak smoke levels of 10% or higher.

Figure 2 illustrates the distribution in peak opacity levels for the buses that were evaluated by a trained observer.

Figure 1

Observation of High Smoke Bus
During Field Survey

Figure 2



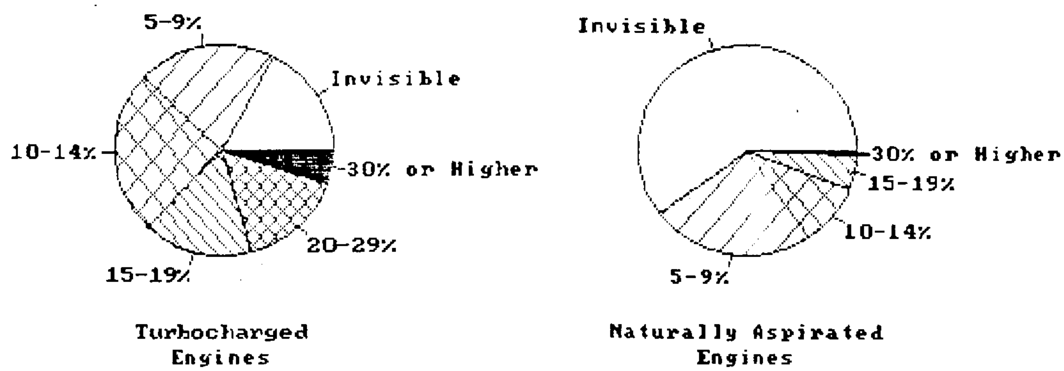
Analysis of Records and Specifications

Turbocharged Engines Emit More Smoke - The study results indicate that there are significant differences in smoke levels that are unrelated to maintenance and fuel quality. In general, late model turbocharged engines have higher smoke levels than older, naturally aspirated (non-turbocharged) engines. For buses observed during the field survey, 60% of all naturally aspirated engines had peak smoke levels that were invisible (<5% opacity) and only 15% of naturally aspirated buses had peak smoke levels of 10% or higher.

For turbocharged buses, only 17% had invisible exhausts and 62% had peak smoke levels of 10% or higher. Figure 3 illustrates the difference between the observed smoke levels of turbocharged and naturally aspirated engines.

Figure 3

OBSERVED SMOKE LEVELS
Turbocharged and Naturally Aspirated Engines



Note: Smoke Levels Shown
Are Peak Opacity Readings

Smokiest Engines Generally Have High Mileage Since Last Maintenance - The results of the study also indicate that maintenance practices appear to have a significant effect on smoke and particulate emissions from Diesel powered transit buses. For engines of a particular type, buses with the highest smoke levels generally had accumulated high mileage since their last injector change or complete engine rebuild. In addition, "maintenance sensitive" engines (such as the GM 6V-92T) demonstrated a much greater range of smoke levels in customer service.

Mileage Since Last Maintenance is a Poor Predictor of Smoke Level - However, an important conclusion reached was that there is no statistically significant relationship between maintenance frequency and observed smoke levels. Engines that had accumulated the highest mileages since smoke-related maintenance generally were the vehicles with the highest observed smoke levels, but many vehicles with high mileage accumulation since last maintenance had very low smoke levels.

Fuel Effects Were Not Apparent - Detailed specifications for the fuel used by the buses that were observed in the field were not available in all cases. However, one of the three transit districts used a 60/40 blend of Diesel Fuel Number 1 (DF1) and DF2, one used exclusively DF1, and the other district used only DF2 grade fuel. There was a fairly detailed analysis for the DF2 fuel that was used by one district. The analysis indicated that this was a "lighter" than average fuel, making it closer to a mixture of DF1 and DF2 than a typical number 2 fuel would be.

To our great surprise, every single engine model in the sample was unique to a particular district. Because of the potential for model-to-model differences in smoke emissions, it was not possible to determine whether fuel differences were a factor.

Literature Review and Consultation

Based on the literature review, the boiling range and aromatics content of Diesel fuel has a significant effect on smoke and particulate emissions. A reduction in the temperature at which 90% of the fuel is distilled and a reduction in the percent of aromatic hydrocarbons contained in Diesel fuel could reduce average particulate emission levels by 25-50%. DF1 fuel consistently has a lower 90% point and lower aromatics content than DF2.

Despite the inability to quantify the effect of fuel grade based on the field survey, all three transit districts involved in the study recognize the significance of fuel quality on smoke and particulate emissions from Diesel engines. Representatives of the districts which used DF2 or blends of DF1 and DF2 said that they would prefer to use DF1 exclusively, were it not for the higher cost of that grade. The maintenance superintendent of the district that uses DF1 exclusively would prefer to use jet fuel.

Conclusions

Mileage accumulation does not appear to be the best means of determining when preventative maintenance should be performed. Many engines continue to demonstrate low smoke levels with very high mileage between maintenance. Based on the study results, the most effective means of ensuring that transit buses receive adequate smoke-related maintenance would be for routine smoke measurements to be incorporated into standard maintenance procedures.

Although a variety of techniques could be used to incorporate routine smoke checks, observation of buses accelerating from a standing start over a 100 meter distance by a trained observer would be totally adequate for identifying problem buses. Smoke meters and expensive chassis dynamometers are not required.

Based on the results of the literature survey and the field observations, it appears that every model of bus observed can have peak emissions below 20% opacity when not in need of maintenance. Buses powered by naturally aspirated engines could comply with a requirement for peak smoke levels to be below 10%.

With a requirement that buses be immediately scheduled for maintenance when their exhaust opacity is equal to or greater than 10% (naturally aspirated engines) or 20% (turbocharged engines), the nuisance of smoky buses could be substantially reduced. In addition, it is estimated that average smoke and particulate emissions from transit buses could be reduced by approximately 35%.

The cost of improved maintenance practices may be low relative to the reduction in particulate emissions that could be achieved; however, further study is required to determine the cost-effectiveness of such an inspection and maintenance program.

For smoke emission control purposes only, requirements for improved Diesel fuel quality would probably be higher in cost than an inspection and maintenance program. However, the cost of improved quality fuel for transit buses is expected to be significantly lower than improvements in all Diesel fuel. In addition, the cost-effectiveness of Diesel fuel specifications depends on whether credit is given to the effect such specifications would have on secondary particulates (i.e., particles formed through the atmospheric transformation of sulfur dioxide into sulfate). Based on our analysis, control of transit bus fuel quality through limitations on aromatics content and 90% boiling point would be cost effective relative to other measures which have been adopted for the control of the total amount of fine particles in the atmosphere. In addition to reducing bus smoke, such controls would improve atmospheric visibility on a regional basis.

Section 2

RECOMMENDATIONS

Based on the survey and analyses performed, the following recommendations are offered for consideration by the California Air Resources Board and the South Coast Air Quality Management District:

1. Incorporation of frequent and routine exhaust opacity measurements into the maintenance schedules for transit buses should be pursued. Standards of 10% opacity for naturally aspirated engines and 20% opacity for turbocharged engines may be feasible for determining when a bus should be pulled from service for smoke-related maintenance. However, a pilot study to determine whether all engines can achieve these limits should be conducted.

2. Specific requirements for maintenance frequency do not appear to be feasible or cost-effective and should not be pursued. The study indicates that the way maintenance is done is at least as important as how frequently it is done. Frequent adjustments of throttle delay mechanisms and injectors are of no benefit if the adjustments are not done in a manner which minimizes smoke emissions. As has been demonstrated for light-duty gasoline powered vehicles, "mandatory maintenance" is inferior to "inspection and maintenance" for controlling emissions.

3. Consideration should be given to the retrofit of improved components during the rebuilding of transit bus engines. Data from the literature and the field survey indicate that design improvements applicable to bus engines have recently been made in the areas of piston ring design, turbocharger matching, and transient fuel injection rate control. Incorporation of this technology on a retrofit basis may represent a practical and cost-effective means of further reducing smoke and particulate emissions from the turbocharged engines which are the highest smoke emitters.

4. Consideration should be given to the establishment of smoke and particulate emission standards for new bus engines. Smoke and particulate emissions from transit bus engines have increased over the last ten years as a result of increased use of turbocharging and changes made to reduce NOx emissions. In the absence of stringent smoke standards, technology has not been applied which could have maintained the relatively low smoke levels achieved with older engines. EPA has recently adopted new particulate emission standards which significantly reduce the smoke and particulate emission levels from transit buses in the future. ARB

should determine whether the new standards represent the most effective control that can be achieved and whether an expedited schedule for attainment might be feasible for California.

5. Regulations governing the 90% boiling point and aromatics content of Diesel fuel for transit bus use should be considered. The ARB staff analysis of the cost-effectiveness of more stringent Diesel fuel specifications indicates that costs per pound of particulate reduced may be very high. However, the ARB analysis appears to be quite conservative. More importantly, cost estimates provided by individual refiners indicated a very high variability in costs from refiner to refiner. This indicates that the cost-effectiveness would improve substantially if the specifications did not apply to all Diesel fuel. Those refiners who are able to provide higher quality fuel more economically could supply a more limited market demand. Because of the potentially lower cost of applying more stringent quality requirements to a limited amount of Diesel fuel, and given the fact that transit buses operate almost exclusively in urban areas, it may be reasonable to consider separate fuel specifications for transit bus use. Using the lower end of the cost estimates provided to ARB for higher quality Diesel fuel, more stringent fuel specifications for transit buses would appear to be a cost-effective means of achieving further smoke and particulate emissions control.

Section 3

INTRODUCTION

The overall objective of this study was to determine whether changes in transit bus maintenance practices could be effective in reducing smoke and particulate emissions. In order to accomplish this overall objective five tasks were planned:

1. Field Survey of Bus Smoke Levels
2. Review of Maintenance Records and Fuel Specifications for Buses Observed in the Field
3. Correlation Analysis of Maintenance Records, Fuel Specifications and Observed Smoke Levels
4. Literature Review and Consultation
5. Analysis of Possible Maintenance Practice and Fuel Specification Changes

Summary of the Work Performed

Field Study - In order to be able to determine whether differences existed between transit districts, buses from three different transit districts were observed. The three districts involved were Southern California Rapid Transit District (RTD), Santa Monica Municipal Bus Lines (MBL), and Sacramento Regional Transit (RT).

The field study of smoke levels was conducted using two principal techniques: video tape recording and the use of a "trained observer". The techniques used by the trained observer were those taught in ARB's "Visual Emissions Evaluation" course, and the observer had been certified as accurate by ARB. The video tapes were used to document the human observations and to assist in subsequently resolving any questions regarding the identification of individual buses. Information regarding bus identification, date, time, location, and the position of the trained observer were recorded on paper and on the sound track of the video tape.

Review of Records - Maintenance records and fuel specifications were assembled for our review by the three transit districts whose buses were observed during the field study. Meetings with the transit districts were arranged by ARB after the field study had been completed. The districts were not made aware of the study until after all of the visual observations had been completed. Numerous telephone conversations with the transit districts were used to clarify the maintenance records that were provided for review.

Correlation Analysis - All data on exhaust opacity, fuel specifications, and maintenance history were prepared for computer analysis using data base management software. Distributions of exhaust opacity levels were constructed for the entire sample of buses and for a variety of subsets of the sample. The subsets were constructed based on transit district, engine model, and fuel specifications. For each subset, regression analyses were conducted between the mileage since certain types of maintenance and exhaust opacity.

Literature Review and Consultation - An extensive literature review was conducted to determine the results of previous studies into the relationship between fuel specifications, maintenance practices, and smoke and particulate emissions from heavy duty Diesel engines. Discussions regarding the importance of certain maintenance practices were also held with representatives of General Motors Corporation, the manufacturer of all of the engines that were used in the buses included in the field survey. In addition, discussions were held with the personnel responsible for maintenance at the three transit districts.

Analysis of Possible Changes - Based on the results of the correlation analysis and the literature review, estimates were made of the effect that certain changes in maintenance practices and fuel specifications would be expected to have on smoke and particulate emissions. Rough estimates of the cost associated with various changes were also made.

Organization of the Report

This report is divided into ten sections. Section 1 contains the Summary and Conclusions, Section 2 presents the Recommendations, and and Section 3 is this Introduction.

Section 4, Factors Affecting Diesel Smoke and Particulates, provides an overview of the many design, operation, maintenance, and fuel differences that determine the smoke emissions from Diesel engines. This section provides a general background for readers who are not familiar with Diesel engines and the factors affecting their emissions of particulate matter.

Section 5, Bus Smoke Emissions in Field Service, covers the results of the field survey. It contains a detailed description of the survey techniques and a summary of the raw data.

Section 6, Maintenance and Fuel Purchase Practices, contains a description of how transit buses are routinely maintained. This section is based on discussions with the transit districts and our review of the detailed maintenance records that were provide by the districts. This section also describes the record keeping procedures that transit districts use in order to keep track of when a vehicle requires maintenance.

Section 7, Data Analysis, describes how the available data were analyzed. This section also shows the results of the analysis of exhaust opacity differences between various subsets of the data base, and the relationship that was observed between maintenance history and exhaust opacity.

Section 8, Literature Review and Consultation, summarizes the available literature on the effect of fuel quality and maintenance practices on exhaust opacity and particulate emissions. This section also discusses the view of the General Motors Corporation and transit district maintenance personnel regarding how maintenance practices can be used to minimize smoke emissions.

Section 9, Prospects for Reducing Smoke and Particulates, contains our analysis of certain changes in maintenance and fuel specifications that would reduce smoke and particulate emissions from transit buses. The analysis includes the estimated cost and cost-effectiveness of the changes.

Section 10 contains a list of references used during the course of the literature review. Throughout this report, numbers appearing in parentheses refer to the references listed in this section.

Appendix A contains a tabulation of the raw data from the visual observations made during the field study and a summary of the vehicle data and maintenance data received from the transit districts. Appendix B contains a tabular summary of the opacity distributions for individual engine models and transit districts. Appendix C contains the detailed results of the regression analyses conducted.

Section 4

FACTORS AFFECTING DIESEL SMOKE AND PARTICULATES

To understand the factors which contribute to particulate emissions from Diesels, it is necessary to be familiar with the Diesel combustion process. With an understanding of Diesel combustion, the effects of engine design features, operational characteristics, maintenance practices, and fuel specifications are easier to comprehend.

Beginning with a description of the Diesel combustion process, this section contains a brief overview of most of the factors which are known to be related to smoke and particulate emissions from Diesel engines. With the background provided in this section, the detailed discussion of maintenance practices and fuel effects covered in the remainder of the report may be easier to follow.

The Diesel Combustion Process

Diesels are compression ignition engines. As with spark ignition engines, the operation of the Diesel engine involve four main events:

1. Intake of a fresh charge of air into a cylinder;
2. Compression of the intake charge;
3. Power generation during the combustion of fuel and air, forcing the piston and connecting rod to turn the crankshaft; and
4. Exhaust of the combustion products from the cylinder.

The heat generated by the compression of air under the relatively high compression ratio (usually 17:1 to 22:1) of a Diesel engine is sufficient to ignite the fuel without the aid of a spark plug. The temperature achieved during the compression of air in the cylinder of a Diesel is affected by both the temperature of the engine and the temperature of the air drawn or blown into the engine. In addition, the temperature at which a fuel will ignite is difficult to precisely control because of differences in the crude oil from which fuels are made and the extraordinary refining costs that would be associated with making all fuels ignite at exactly the same temperature and pressure. Because of these variables, it is not possible to precisely control when the temperature necessary to initiate combustion will be achieved during the compression stroke.

For optimum engine performance, it is necessary to initiate the combustion of the fuel just before the end of the compression stroke. Earlier ignition would cause the burning fuel to work against the piston as it is still rising in the cylinder. Later ignition would not allow for maximum heat release to occur while the piston is still near the top of its expansion or "power" stroke.

Because of these considerations, Diesel engines are designed with a significant margin of safety for the temperature that will be achieved just before the end of the compression stroke. The compression ratio must be high enough that ignition temperature will be achieved during cold weather and before the engine is fully warmed-up. However, this means that under most operating conditions, the ignition temperature will be achieved before it is needed to ignite the fuel at just the right moment. Because of this, the fuel must not be injected into the cylinder until just before the moment when combustion should begin.

(In contrast, spark ignition, gasoline engines do not have high enough compression ratios to cause auto ignition of the fuel. The fuel can therefore be mixed with the intake air and brought into the cylinder well before the point where the start of combustion should occur. At the right moment, the spark plug is fired, and the fuel air mixture is ignited.)

Because the fuel must be injected into the Diesel engine just before the start of combustion, it is not possible to achieve a uniform mixing of the fuel and air. The tiny droplets of fuel sprayed into the cylinder by the fuel injector begin to burn before they are completely vaporized and mixed with the air in the cylinder.

It is this non-homogeneous, droplet combustion process that is the source of carbonaceous particulate emissions from Diesel engines.

Origins of Directly Emitted Particulates

Near the vaporizing droplets, there is insufficient oxygen to completely burn all of the fuel. Rather than burning the fuel completely, to form carbon dioxide and water vapor, there are very high levels of carbon monoxide formed. As explained by Behrens (1), reactions between the carbon monoxide molecules can form solid carbon by the following reaction:

$$2\ CO = CO_2 + C\ (solid) + 40\ K\ cal$$

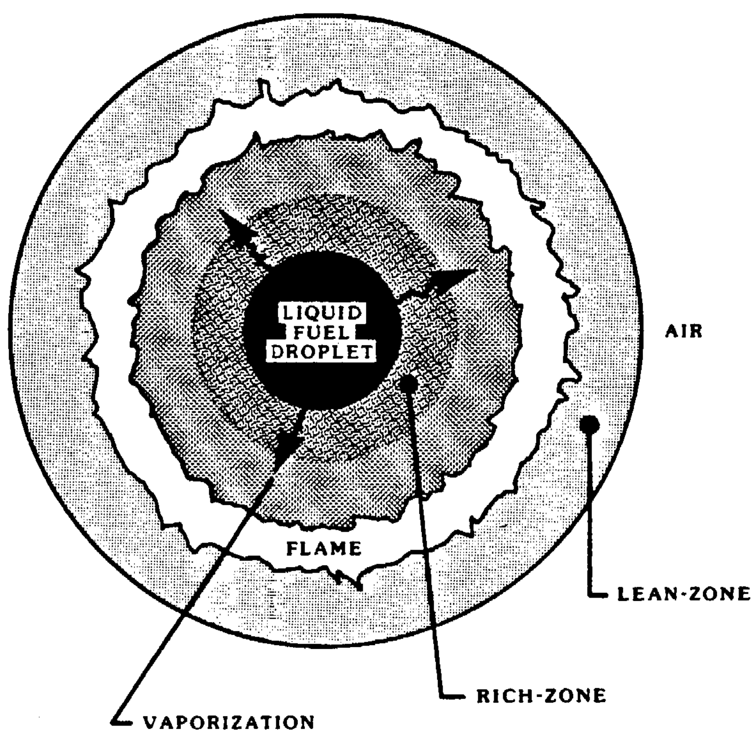
Any remaining carbon monoxide is easily oxidized to carbon dioxide as turbulence within the combustion chamber brings oxygen into contact with the carbon monoxide. However, the solid carbon does not react as easily with oxygen and some of the carbon formed during the earlier phase of the combustion process is exhausted as soot. (It should be noted that numerous other processes leading to soot formation have been suggested. Some involve a very complex chain of reactions. However, the literature indicates that pyrolysis and combustion occurring in fuel-rich regions in the combustion chamber are key to high levels of soot emissions.)

Although fuel characteristics are a factor, high soot formation potential is an inherent feature of the droplet combustion process. If the compression ratio is sufficient, warmed-up Diesel engines will also burn gasoline (2). Significant soot formation still occurs when gasoline is the fuel (2).

Figure 4 illustrates the non-uniform nature of the air-fuel mixture that exists in the vicinity of a vaporizing fuel droplet.

Figure 4

AIR FUEL DISTRIBUTION
AROUND BURNING FUEL DROPLET



Most factors that affect directly emitted particulate from Diesel engines are related to 1) the amount of combustion that occurs in fuel-rich regions of the cylinder, and 2) the opportunity of carbonaceous combustion products created in the rich-zone to be subsequently oxidized as more mixing occurs in the cylinder. "Rich-zone" combustion is the key.

Secondary Particulates

In addition to the emissions of directly emitted particulates discussed above, Diesels, like all other combustion sources, also contribute to the formation of "secondary" particulates in the atmosphere. Secondary particulates are particles formed from the atmospheric reactions of certain gaseous emissions. Oxides of nitrogen (NOx) and sulfur dioxide (SO_2) are the two principal "precursors" of secondary particulate from Diesel engines.

Sulfates and nitrates have little effect on the opacity of engine exhaust because there is little of these compounds in the exhaust as it leaves the engine. However, in the atmosphere, SO_2 and NOx emissions are transformed into sulfate and nitrate particles. Sulfates and nitrates are significant contributors to the regional visibility degradation that is apparent in such areas as the South Coast Air Basin.

SOx emissions from Diesel engines are directly related to the sulfur content of the fuel. About 97% of the sulfur contained in the fuel is converted to sulfur dioxide in the combustion process (3). The remainder is further oxidized to sulfate (SO_4). The sulfur contained in fuels used in other engines (e.g., gasoline engines) also contributes to sulfate in the atmosphere. However, Diesels are a particular problem because Diesel fuel sulfur levels tend to be much higher than the sulfur levels in gasoline.

NOx emissions from Diesel engines are also related to fuel quality but there are many other factors which affect NOx emissions as well. The nitrogen content of the fuel is a factor, since fuel nitrogen can be converted into nitrogen oxide in the combustion process. However, the principal source of Diesel engine NOx emissions is the nitrogen and oxygen contained in the air ingested by the engine.

The high temperatures which occur during combustion cause some of the nitrogen and oxygen to combine to form nitric oxide (NO). The amount of NO formation depends on the magnitude of the combustion temperature, the time during which peak temperatures occur, and the concentration of oxygen available in the zone where the peak temperatures occur.

Diesel Engine Design Features

Figure 5 is a schematic of one cylinder of a Diesel engine, showing the typical location of the fuel injector and the four phases of the

"4-cycle" engine combustion process. Figure 6 illustrates the 2-cycle combustion process using a schematic of a "through-scavenged" engine of the type used in most buses. With this type of engine, there is no separate "intake" stroke and "exhaust" stroke.

The intake and exhaust process in a 2-cycle engine occurs at the end of the "power" stroke and just before the beginning of the "compression" stroke. As the piston nears the bottom of its travel, the exhaust valves are opened and intake ports are uncovered. High pressure air from the blower pushes the exhaust gas up the cylinder and out the exhaust valves. As the piston starts moving back up the cylinder, the intake ports are closed off, the exhaust valves are closed and the compression of the fresh air that was blown into the cylinder begins. Near the top of the compression stroke, fuel is injected and the piston then starts to travel back down the cylinder during the power stroke.

For 2-cycle engines manufacturered by the General Motors Detroit Diesel Allison (DDA) Division, there is a standard convention used to describe each engine: a number, followed by a letter, followed by another number, followed by another letter. The first number is the number of cylinders. The first letter is the configuration of the engine ("V" for cylinders layed out in a Vee configuration, and "L" for in-line engines). The second number is the cubic inch displacement of each cylinder. The second letter denotes whether the engine is turbocharged (T) or naturally aspirated (N). Using this convention, a "6V-92T" engine has six cylinders in a Vee configuration, 92 cubic inches per cylinder, and a turbocharger.

Figure 5

4-CYCLE DIESEL

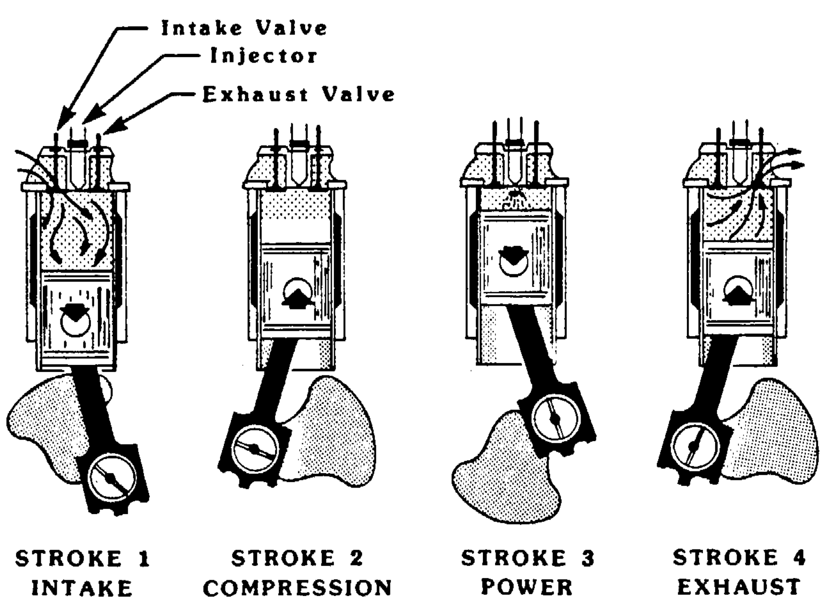
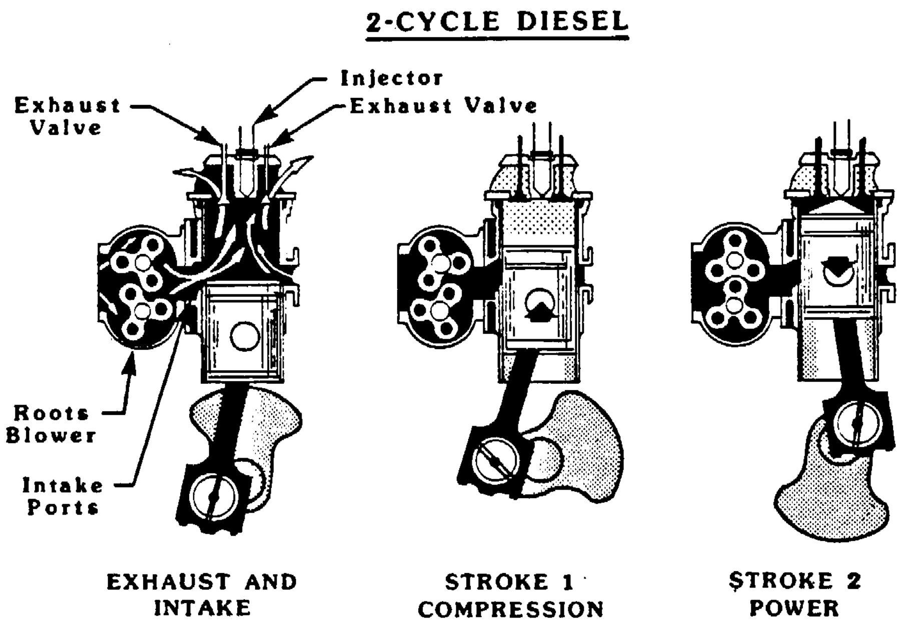


Figure 6



Effect of Design Variables

Engine design variables that affect particulate emissions from Diesel engines include: injector spray pattern, injection pressure, injector geometry, injection timing, injection rate, fuel delivery response characteristics, turbocharger response characteristics, minimum air/fuel ratio, and cylinder head, combustion chamber and piston crown design.

All of these factors can affect the amount of rich-zone combustion that occurs in the cylinder. For example:

- injector spray pattern determines how well the fuel will be mixed with the air in the cylinder;

- injection pressure determines how fine the droplets will be (with smaller droplets being easier to vaporize and mix with air before combustion begins);

- injector geometry determines the volume of fuel that dribbles out of the injector in between injection events (and therefore does not mix well with air);

- injection timing determines what peak combustion temperatures will be and how hot the partially burned fuel will be during the expansion stroke when there is the opportunity for the further oxidation of soot particles formed early in the combustion process;

- fuel delivery and turbocharger response characteristics determine how well the air and fuel will be matched for achieving the optimum overall air/fuel ratio needed to minimize rich-zone combustion;

- the maximum rate of fuel injection determines the minimum overall air/fuel ratio and therefore the amount of fuel which is burned in rich-zones; and

- cylinder head, combustion chamber and piston crown geometry determines the amount of mixing that occurs due to swirl or turbulence.

Effect of Maintenance Practices

Lack of adequate maintenance can have similar effects on rich-zone combustion to many of the design variables discussed above. For example:

- eroded injector tips can disrupt the spray pattern, and reduce the degree of atomization and fuel air mixing that is achieved;

- broken or worn rings can allow more lubricating oil to enter the combustion zone thereby reducing the overall air/fuel ratio and introducing a more difficult to burn hydrocarbon into the process;

- worn blowers can reduce the amount of air ingested by the engine thereby reducing the air/fuel ratio and increasing the amount of rich-zone combustion;

- defective or misadjusted throttle delay valves can allow too much fuel to be injected before the turbocharger is delivering an adequate supply of air to the cylinder;

- improper injector adjustments can increase the maximum fuel delivery rate, thereby enrichening the engine;

- dirty air cleaners reduce the air ingestion and also enrichen the overall mixture;

- worn valves or valve seats can allow the leakage of high particulate concentrations formed early in the combustion process before there has been an opportunity for the particulate to mix with air in the cylinder and possibly be further oxidized; and

- retarded injection timing can reduce the peak temperature achieved, thereby making it increasingly difficult to oxidize carbon particles that are formed early in the combustion process when they are eventually mixed with air.

Effect of Operational Variables

Operational variables that affect particulate emissions from Diesel engines include: engine speed and load, ambient temperature, altitude, and the rate of acceleration.

At any given engine speed, and with any given amount of boost provided by a turbocharger, there is a certain amount of air ingested by the engine. Therefore, the load on the engine (power demand) will determine how much fuel must be injected into the available amount of air. The load will therefore affect the overall air/fuel ratio of the engine, and the amount of combustion that occurs in rich-zones. At lighter loads there is a greater ratio of air to fuel, less rich zone combustion, and less smoke. At higher loads, the reverse is true.

Ambient temperature also affects the air/fuel ratio of the engine because of the change in air density that occurs with changes in temperature. Operation of a Diesel engine in very hot weather can increase smoke emissions because of the reduced density of the air ingested.

Increasing altitude also reduces air density, which is why Diesels smoke more when traveling in mountainous regions.

The rate at which a Diesel powered vehicle is accelerated can effect smoke emissions because higher acceleration rates put a higher load on the engine and thereby reduce the air/fuel ratio. However, a second effect of acceleration rate is a factor with turbocharged engines. Since turbochargers are run off of exhaust energy, they turn at a relatively low speed under idle and very light load conditions. When power is applied, it takes some time for the turbocharger speed to increase to the point where it is supplying additional air to the engine. During this "delay" or "lag" period, the engine tends to have a shortage of air and an excess of fuel, leading to additional rich-zone combustion. (Throttle delay mechanisms are incorporated in some Diesel engines to minimize this problem by not allowing the fuel rate to increase instantaneously.)

Relevant Diesel Fuel Characteristics

Compared to gasoline, Diesel fuel has heavier, longer chain molecules. Gasoline contains such light and volatile compounds as butane (four carbon atoms) and pentane (five carbon atoms). The heaviest hydrocarbons contained in gasoline are distilled off at about 400°F. These heavier hydrocarbons generally contain about twelve carbon atoms. In contrast, the lightest hydrocarbon molecules contained in Diesel fuel have a boiling point that approximately equals the heaviest molecules in gasoline. The hydrocarbons in Diesel fuel generally contain twelve to twenty-two carbon atoms. These molecules have a boiling range of about 350°F to 650°F.

The two most common grades of Diesel fuel are Diesel fuel #1 (DF1 or 1-D) and Diesel fuel #2 (DF2 or 2-D). Characteristics of DF1 and DF2 used in the certification of Diesel engines are controlled as shown in Table 1.

Recommended specifications for Diesel fuels have also been published by the American Society for Testing and Materials (ASTM). Using the same format used to display the certification fuel specifications, the ASTM specifications for DF1 and DF2 are shown in Table 2.

As shown in Table 2, Diesel fuels are generally less well defined by the ASTM specifications. In addition, it is apparent that the ASTM specifications allow the use of significantly higher 90% boiling points and lower cetane values.

Table 1

Specifications for Emissions Certification Diesel Fuels

	DF1	DF2
Cetane Number	48-54	42-50
Distillation Range:		
initial boiling point, °F	330-390	340-400
10 percent point	370-430	400-460
50 percent point	410-480	470-540
90 percent point	460-520	550-610
end point	500-560	580-660
Gravity, °API	40-44	33-37
Total Sulfur, percent	0.05-0.20	0.2-0.5
Aromatic Hydrocarbon Content, min. percent . .	8	27
Paraffins, naphthenes, olefins, percent	remainder	remainder
Flashpoint, °F (minimum)	120	130
Viscosity, centistokes	1.6-2.0	2.0-3.2

Table 2

ASTM Specifications for Diesel Fuel

	DF1	DF2
Minimum Cetane Number	40	40
Distillation Range:		
initial boiling point, °F	--not specified--	
10 percent point	--not specified--	
50 percent point	--not specified--	
90 percent point	550 max.	540-640
end point	--not specified--	
Gravity, °API	--not specified--	
Maximum Sulfur, percent	0.5	0.5
Aromatic Hydrocarbon Content, min. percent	--not specified--	
Paraffins, naphthenes, olefins, percent	--not specified--	
Flashpoint, °F (minimum)	100	126
Viscosity, centistokes	1.3-2.4	1.9-4.1

This comparison is significant because fuels sold in California (except for the sulfur content of Diesel fuel produced by large refiners in the South Coast Air Basin) are generally blended to meet ASTM specifications, not the specifications which apply to certification fuels. Because fuel specifications affect emission levels, it is clear that ASTM specifications do not ensure that vehicles will meet the emission standards in customer service.

According to the results of a survey conducted by ARB, the following characteristics represent the average Diesel fuel being sold in California during 1984:

Sulfur content	0.23%
Aromatics content	33%
90% boiling point	611°F

As discussed in greater detail in Section 8 of this report, sulfur content, aromatics content, and 90% boiling point are all related to the particulate emissions of Diesel engines. Fuels with higher sulfur contents result in higher emissions of sulfate particles. In addition, the higher sulfur dioxide emissions that result from the combustion of higher sulfur fuel also increase the formation of "secondary" particulates (sulfate) in the atmosphere.

Fuels with higher 90% boiling points tend to produce higher particulate emissions, probably because the heavier molecules contained in such fuels are more difficult to vaporize and mix with the air. A high aromatics content is also conducive to the formation of greater amounts of particulate emissions.

Effect of Production Techniques on Diesel Fuel Characteristics

The simplest way to produce Diesel fuel is from the distillation of crude oil. All of the hydrocarbons necessary to form Diesel fuel occur naturally in crude oil, and those molecules which are boiled off between 350°F and 650°F generally produce a blend which meets the ASTM specifications for Diesel fuel. Diesel fuel produced only through distillation is referred to as "straight-run" Diesel fuel.

However, many of the molecules contained in straight-run Diesel fuel can also be used to make gasoline if they are "broken" into lighter weight molecules through the use of thermal cracking, catalytic cracking, or hydrocracking processes. In addition, many of the molecules contained in straight-run Diesel fuel are also usable in jet fuel. The relative demand for gasoline and jet fuel is such that it makes sense for refiners to use some of the straight-run Diesel fuel to produce these lighter weight products. Furthermore, the distillation of crude oil generally produces an excess of molecules which are heavier than those in the Diesel fuel range. These heavier molecules can be converted into Diesel fuel through thermal, catalytic, or hydrocracking processes.

Straight-run Diesel fuel is relatively low in aromatics content and relative high in sulfur content. Diesel fuel produced by hydrocracking is relatively low in aromatics and low in sulfur. However, Diesel fuel produced by thermal and catalytic cracking are relatively high in sulfur content and aromatics.

Significance of Diesel Particulate

Without additional regulation, the ARB staff has estimated (4) that directly emitted particles from Diesel engines in 1990 will account for 7% of all directly emitted particles less than 10 microns in diameter in the South Coast Air Basin. By 1990, Diesels are projected to account for 17% of total sulfur dioxide emission in the SCAB as well. Diesel NOx is projected to be 25% of total NOx emissions.

Although transit buses account for a relatively small fraction of total Diesel emissions (less than 10%), they are part of a category that warrants further attention, and techniques that reduce emissions from transit buses will generally be applicable to other heavy duty Diesel powered vehicles.

Section 5

BUS SMOKE EMISSIONS IN FIELD SERVICE

The field survey of exhaust opacity from transit buses in routine service included buses operated by three transit districts: Southern California Rapid Transit District (RTD), Santa Monica Municipal Bus Lines (MBL), and Sacramento Regional Transit (RT). These districts were selected for the following reasons:

1. Southern California Rapid Transit District operates the largest fleet of transit buses in the state, and RTD's buses are used exclusively in the South Coast Air Basin, the region with the most serious particulate air pollution problems.

2. Santa Monica Municipal Bus Lines operates a much smaller fleet of buses, also used exclusively in the South Coast Air Basin. The inclusion of MBL provided an opportunity to compare a relatively small transit district maintenance operation to the huge RTD operation.

3. Sacramento Regional Transit operates an intermediate size fleet of buses in the Sacramento area. Although the particulate air pollution problem in the Sacramento area is much less severe, it was believed, based on casual observations, that the buses operated by RT typically emitted lower smoke levels than the buses operated by MBL and RTD. In addition, RT's buses operate in the vicinity of the contractor's office. This enabled the field survey techniques to be developed and refined without incurring any travel costs.

Field Survey Methodology

Control of Variables - Although the overall purpose of the study was to determine the effect of maintenance practices and fuel quality on smoke and particulate emissions, it was recognized that many other factors also affect smoke levels from Diesel engines. As discussed in Section 4, these factors include:

1. engine operating temperature;
2. basic engine design characteristics (e.g., injector spray pattern, injection pressure, combustion chamber design);
3. minimum air fuel ratio;
4. engine speed and load;
5. altitude; and

6. fuel delivery and supercharger response characteristics.

Since the study was limited to transit buses operating in the South Coast Air Basin and in Sacramento, it was possible to account for all of these complicating factors. For example, altitude was not a factor because all of the observations were made near sea level. Engine operating temperature was not a factor because all of the observations occurred several miles from the garages where the buses are kept overnight. Engine differences were a factor, however, all of the engines were produced by one manufacturer (General Motors) and all of them used the same basic combustion system (i.e., through scavenged, 2-cycle, direct injection) with very similar geometry. Other differences related to injector capacity, turbocharging, after-cooling, displacement, etc., could be accounted for because there were a limited number of specific engine models to deal with.

The effect of engine speed and load was dealt with by restricting all observations to full power accelerations from a dead stop. Fortunately, this is a relatively easy operating mode to identify and it is the mode of operation that most frequently generates peak smoke levels. In discussions with transit officials, we were assured that full power or near full power accelerations are generally used when buses pull away from a stop and attempt to keep up with the flow of traffic. Part load accelerations are generally only used in heavy traffic when the path of the bus is blocked by traffic.

Observation Techniques - Bus exhaust opacity was measured visually by a qualified observer certified at the Smoke School conducted during June of 1984 by the California Air Resources Board. Using the ARB recommended procedures, plume opacity is defined as the relative amount of light attenuated by the plume or plume "density". Opacity of black smoke plumes is visually measured on a relative basis using the Ringelmann scale. The following specific procedures were followed:

1. Black smoke is read in densities and recorded in the appropriate Ringelmann numbers and fractions (one-quarter increments).

2. The observer should be positioned at a distance sufficient to provide a clear view of the emissions, but not more than one quarter of a mile distance.

3. The light source (sun) should be oriented within a 140 degree sector to the observer's back during daylight hours.

4. Readings should be made approximately at right angles to wind direction.

5. Observations should be made at the point of greatest opacity in that portion of the plume where condensed water vapor is not present.

In addition to the visual measurements, a video camera operated by a second observer was used to film and document the bus exhaust plumes.

Site Selection Criteria - The locations at which the observations were conducted were chosen based on several considerations:

1. Curbside bus stops were determined to be better locations than intersections with traffic lights or stop signs because buses with conventionally located tailpipes (below rear chassis) not traveling in the curbside lane could be obstructed by other vehicle traffic.

2. Visual measurements were always conducted with the sun oriented within a 140 degree sector to the observer's back.

3. During periods of observation when a wind was detected, visual readings were conducted at roughly right angles to the wind direction to ensure a lateral view of the plume.

Other considerations in evaluating locations included selecting bus stops with high bus throughput, low pedestrian traffic and no curbside obstructions such as trees or newspaper stands.

Data Recording Procedures - Generally, bus observations proceeded as follows. As a bus reached a bus stop, observer A (visual measurement) walked beyond the back of the bus to read and record the bus number and the location of the vehicle's tailpipe, either below or at the top of the rear of the chassis. This information was relayed to observer B (video camera) as both observers took positions roughly perpendicular to the back of the bus and approximately 15 feet away.

When the bus pulled away from the stop, observer A made a visual measurement and observer B filmed the bus and plume (if present) as the vehicle proceeded down the street. If the bus number was not clearly visible through the camera, observer B verbally recorded the bus number on the audio track of the videotape.

At some locations, a nearby traffic light or a bus stop across the street made it possible to conduct additional observations of buses traveling on the other side of a two-way street. For these measurements, the same procedures were followed, except the observation distance was between 80 and 100 feet.

In choosing a specific location for observing and filming bus exhausts, we first looked at the location of the bus stop in relation to a stop sign, low pedestrian traffic, and no obstructions on the sidewalk or in the background to interfere with the observations and filming. To maximize the number of our observations, we also looked for a street wherein we could observe buses on both sides of the street, catching those at the bus stop, as well as those on the opposite side of the street at the stop sign or light.

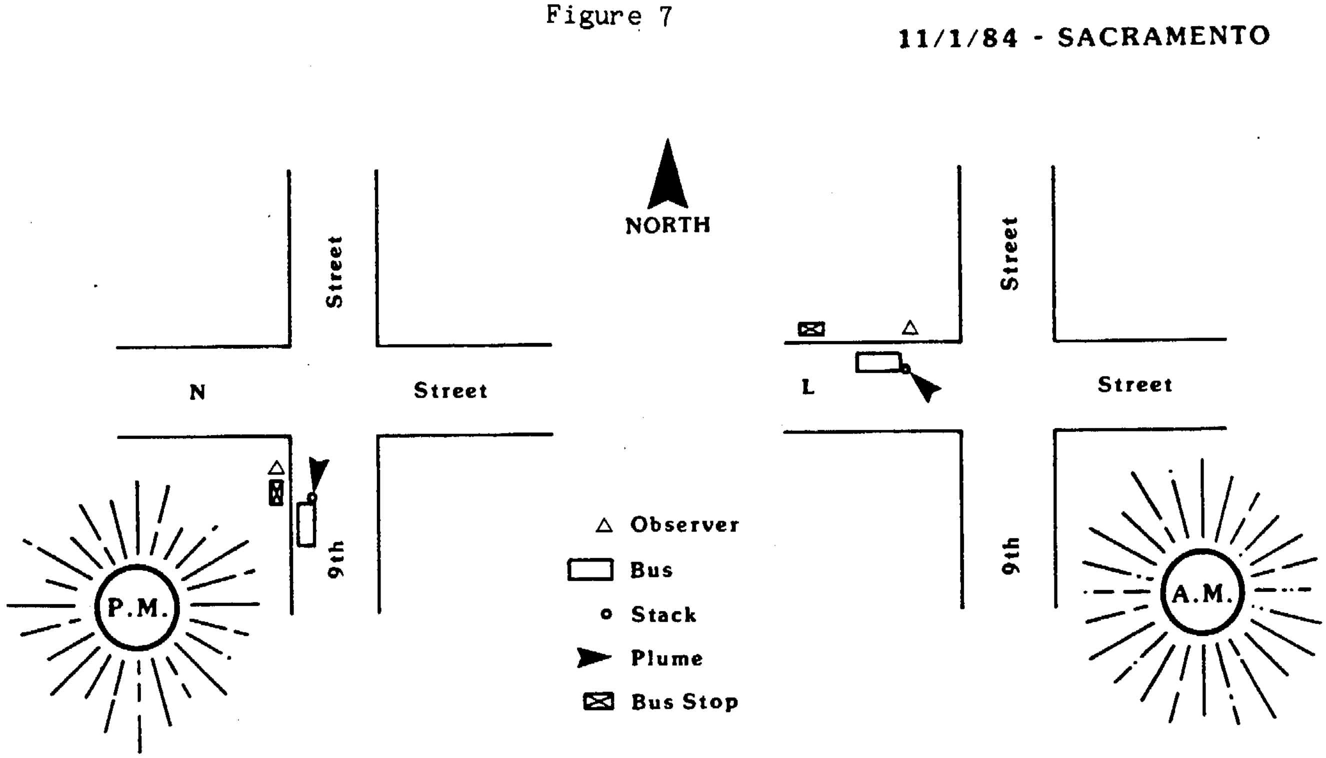
The locations were chosen where the sun would be to the observer's back. We were approximately 15' from the back of the buses at the bus stop, and approximately 80' from those at the stop sign/light on the opposite side of the street. The readings were taken at the time of initial take-off from the bus stop and/or stop sign/light.

Sacramento Regional Transit

On November 1, 1984, the location chosen for the early morning observations was L Street, at the intersection of 9th and L Streets (see Figure 7). At this location, observations were made of the buses heading west, as they pulled away from the bus stop. The sky was clear, the temperature was approximately 50°F, and there was no wind.

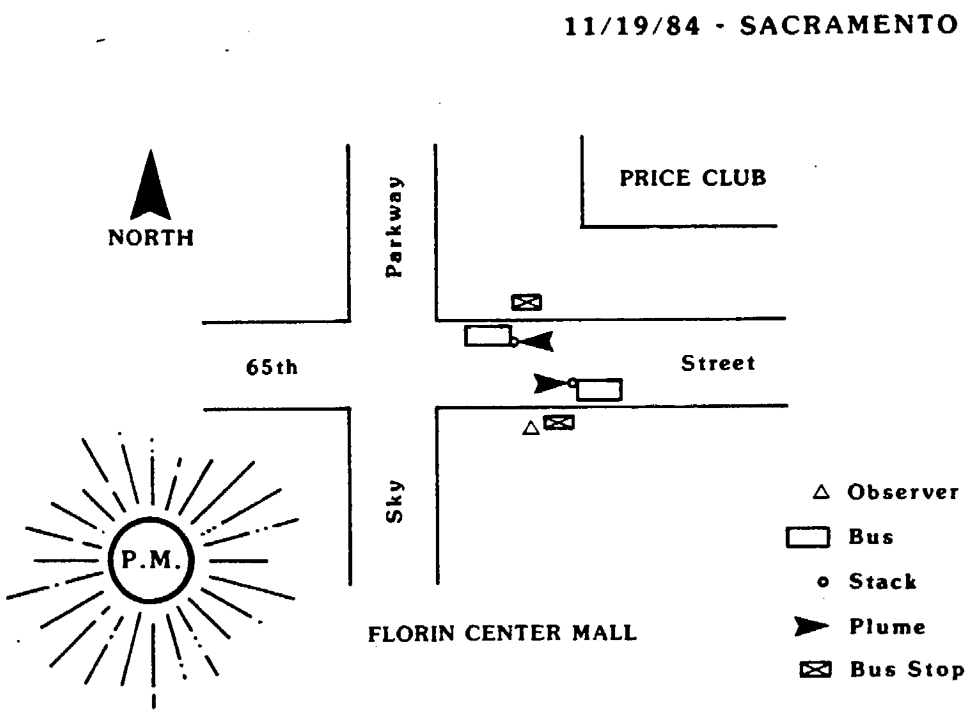
Also on November 1, the location we chose for our afternoon observations was 9th Street, at the intersection of 9th and N Streets (see Figure 7). Buses were observed heading south, as they pulled away from the bus stop. The sky was overcast, the temperature was approximately 65°F, and there was a breeze of approximately 3 mph from the southwest.

Figure 7



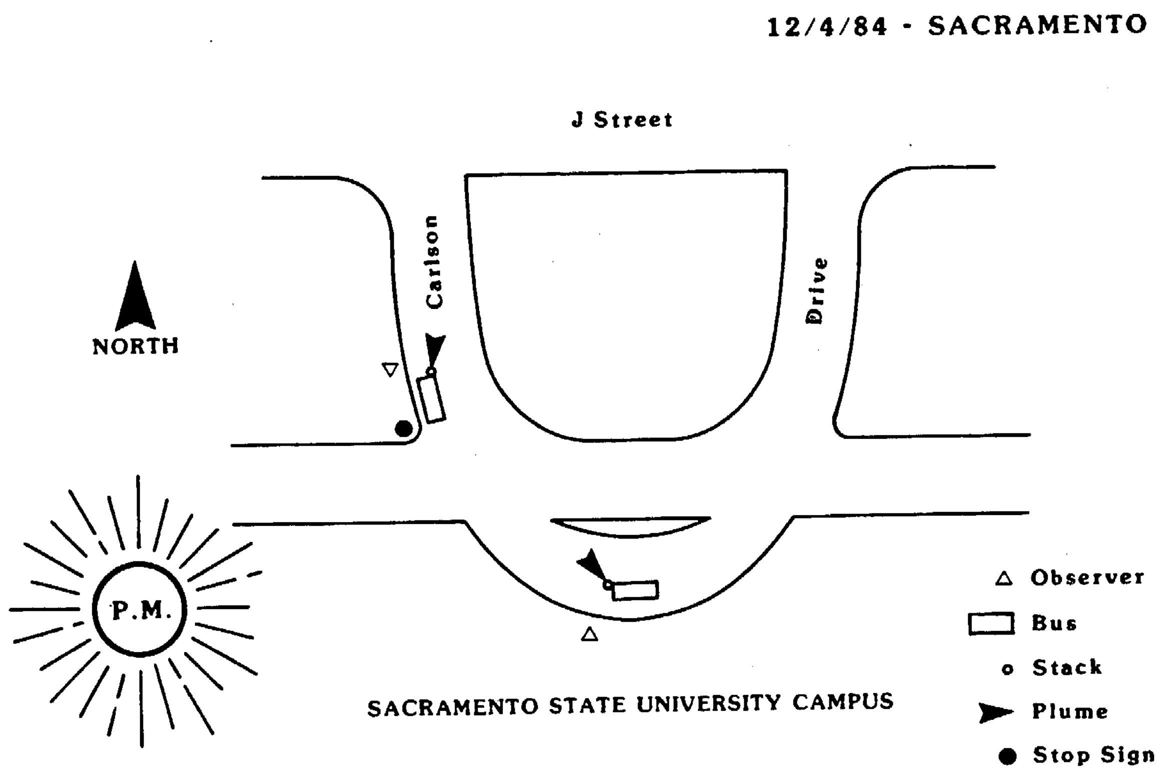
On the afternoon of November 19, 1984, the location of the 65th Street Transit Center on the south side of 65th Street at Florin Center was selected (see Figure 8). At this location, buses were observed heading east as they left the bus stop, and also heading west at the intersection of 65th Street and Sky Parkway as they left the stop light. The sky was clear, the temperature was approximately 45°F, and there was a slight easterly wind from 2-7 mph.

Figure 8



On the afternoon of December 4, 1984, the California State University Sacramento Transit Center at the south end of Carlson Drive was the selected site (see Figure 9). Buses were observed as they were leaving the Transit Center stop, and then as they pulled away from the stop sign on Carlson Drive at CSUS. The sky was overcast, the temperature was approximately 48°F, and there was no wind during these observations.

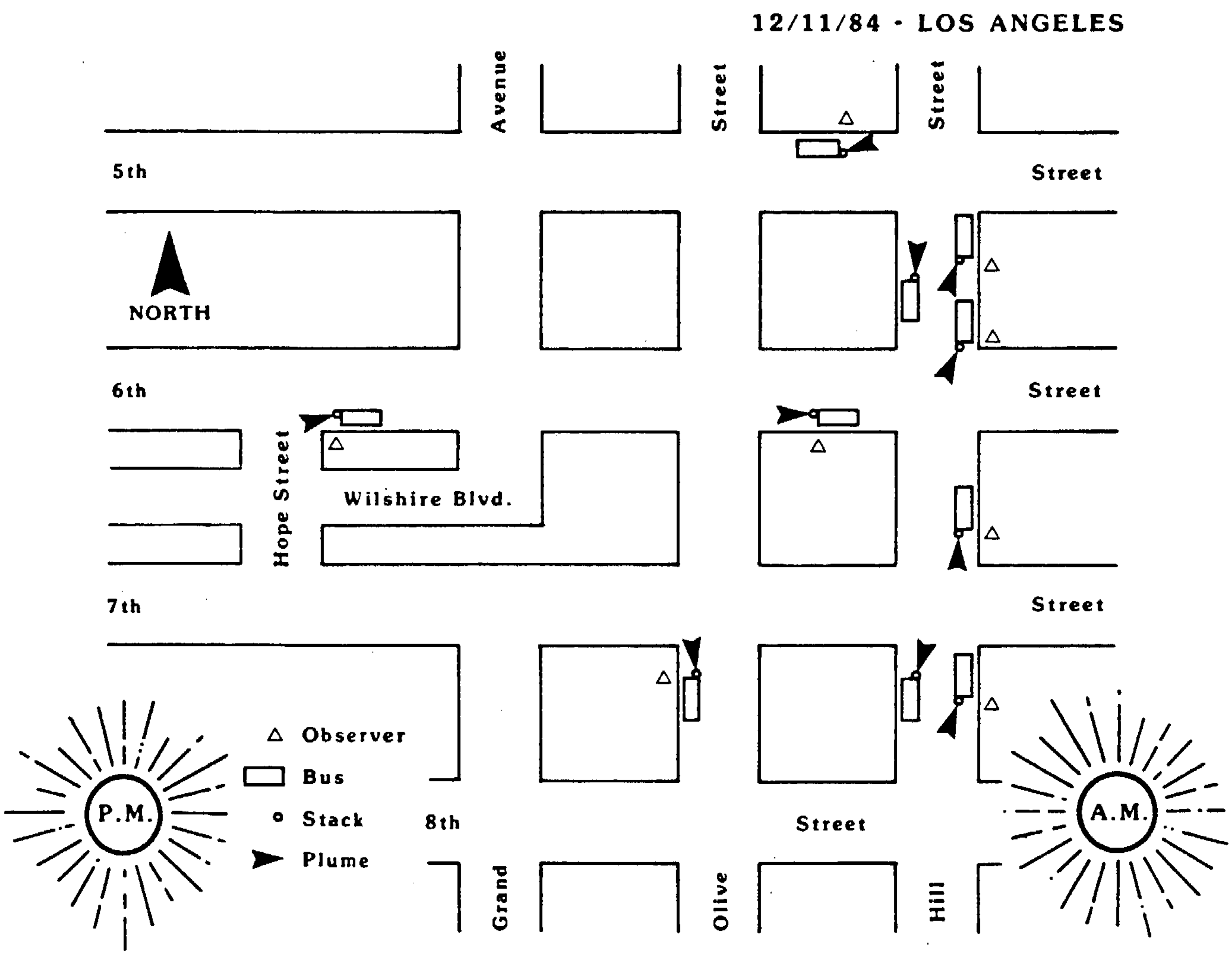
Figure 9



Southern California Rapid Transit District

On December 11, 1984, observations were made, both in the morning and afternoon, at several locations in the downtown Los Angeles area (see Figure 10). In the morning, it was partly cloudy, approximately 60°F, and there was no wind. In the afternoon, the sky was clear, the temperature was approximately 62°F, and there was a slight breeze of 3-5 mph. During the observations in downtown Los Angeles, locations were changed several times in order to maximize the number of buses observed. As shown in Figure 10, buses were observed travelling north, south, east and west.

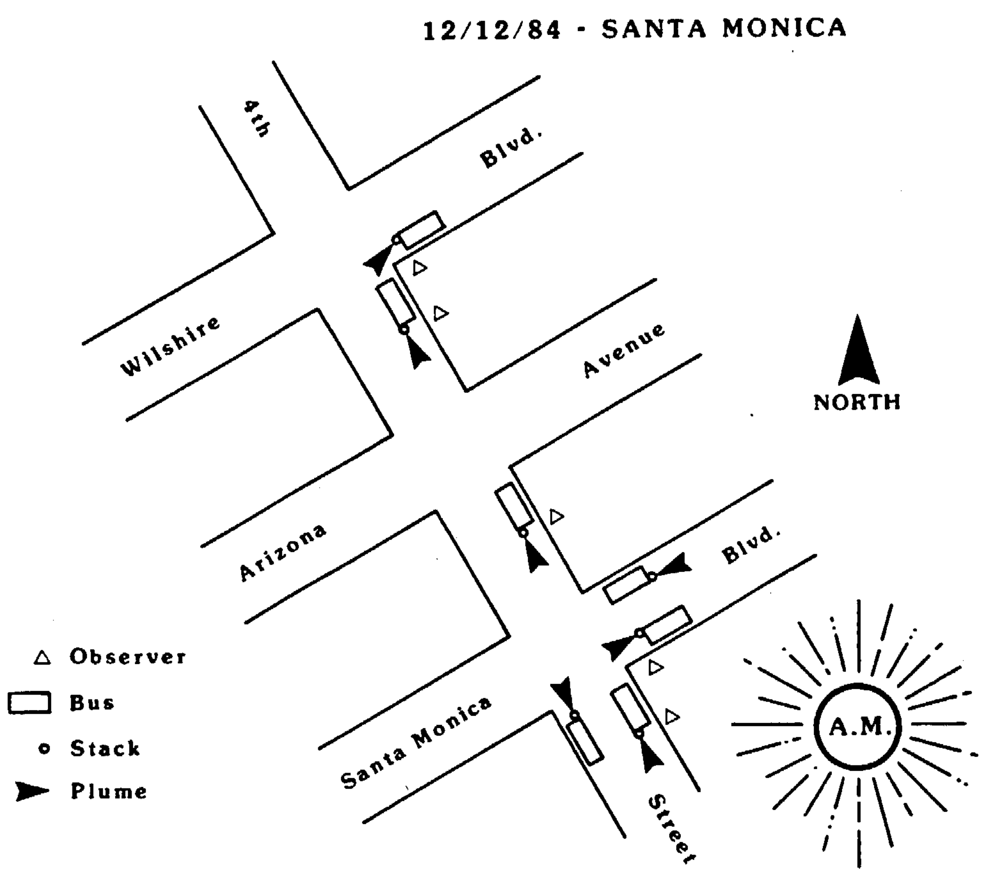
Figure 10



Santa Monica Municipal Bus Lines

On December 12, 1984, observations were made at three intersections: 4th Street and Wilshire Blvd., 4th Street and Arizona Avenue, and 4th Street and Santa Monica Blvd. (see Figure 11). The sky was partly cloudy, the temperature was approximately 50°F, and there was no wind. By moving to three different locations, the number of buses observed was maximized, and buses were observed travelling north on 4th Street and east on Wilshire Blvd.; north on 4th Street at Arizona; and north and south on 4th Street, and east and west on Santa Monica Blvd.

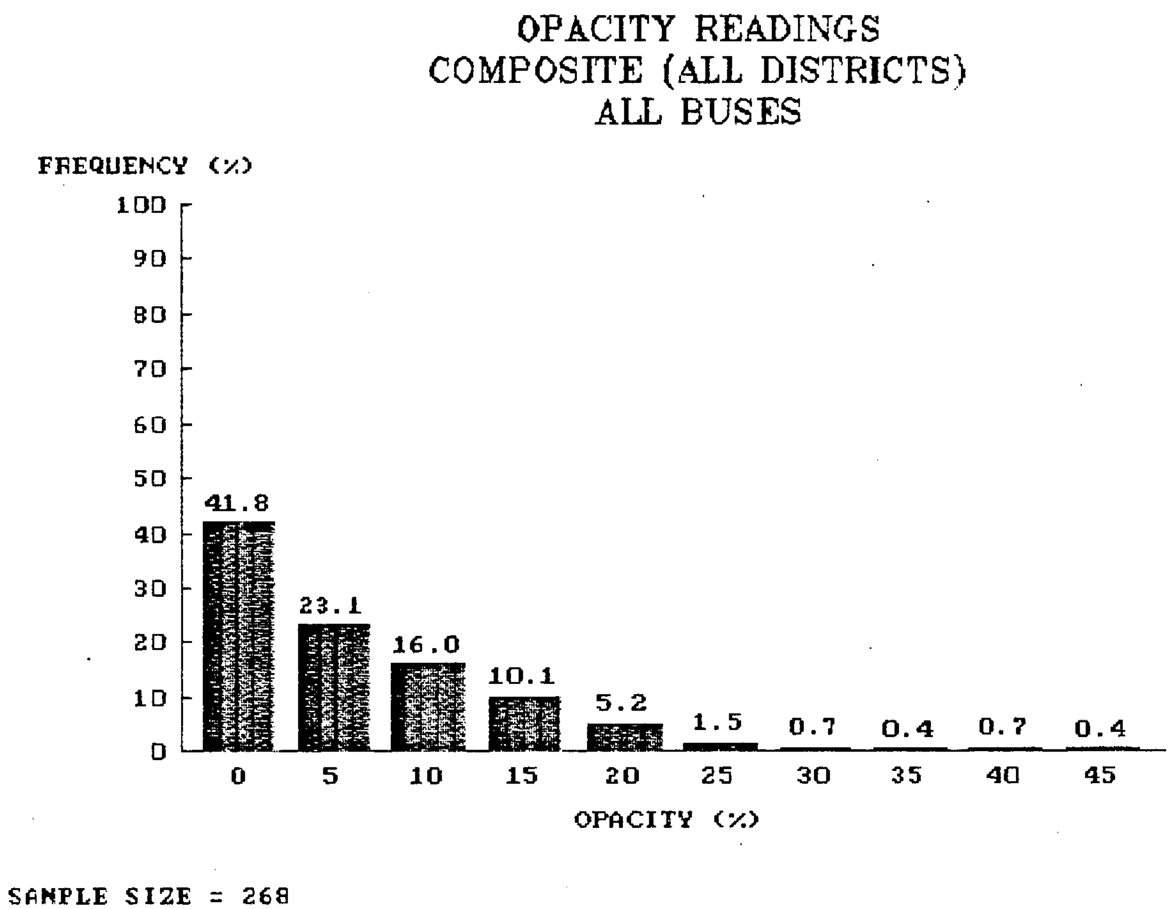
Figure 11



Field Survey Results

During the course of the survey, opacity observations were made for a total of 269 different buses. Appendix A contains the results of the opacity levels recorded for each individual bus. The distribution of all measurements is shown in Figure 12.

Figure 12



As indicated in Figure 12, there was a very wide range of smoke levels observed. 41.8% of the buses had invisible exhausts and the highest opacity was recorded for one bus that exhibited 45% opacity.

Figures 13, 14, and 15 show the opacity distributions for the three individual transit districts. All have a peak occurring at 0% opacity. Except for one bus that was deleted from the sample, all of Sacramento RT's buses were below 20% opacity. Southern California RTD and Santa Monica MBL had buses as high as 40-45% opacity.

(The one Sacramento RT bus that was omitted from the sample exhibited 30% opacity. This bus was omitted because it was observed just after it had experienced a catastrophic engine failure. Available evidence indicates that this bus was not emitting visible emissions just prior to the failure and it was removed from service on the same day we observed it. It was therefore not considered representative.)

Validation of Smoke Reading Accuracy

During the course of the field survey, forty-seven buses were observed on more than one occasion. In all, there were 112 observations that could be compared to another observation on the same bus. In most cases, the duplicate observations all occurred on the same day. In some cases the time between the observations was as much as one month.

Analysis of these duplicate observations indicates the consistency of the visual observation techniques that were used. The average difference between the individual readings on each bus and the average of all readings on the bus was only 2.5% opacity. The standard deviation of the differences between individual readings and the mean was 2.9% opacity.

The consistency between separate readings on the same bus indicates that the techniques employed and the accuracy of the observer were quite good.

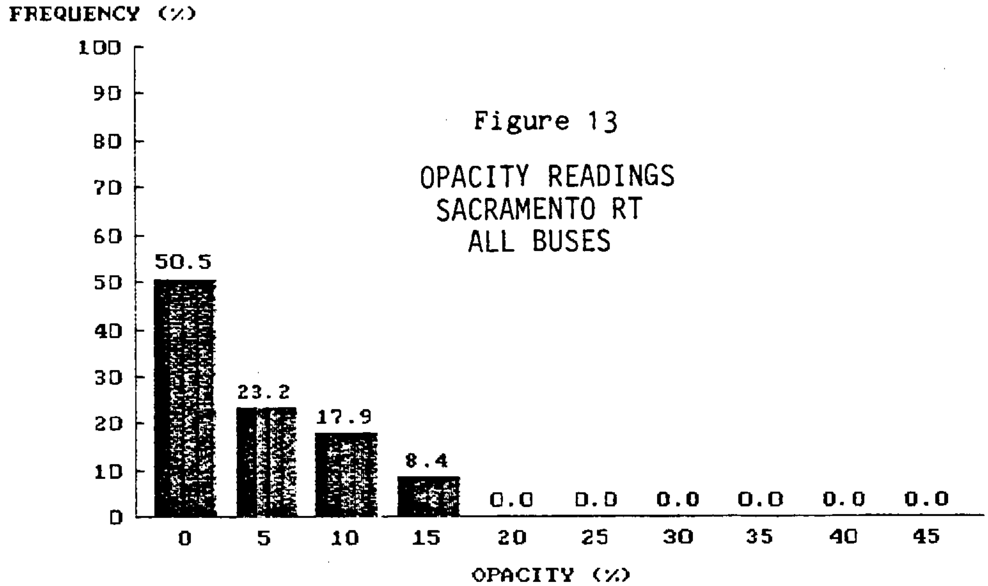


Figure 13

OPACITY READINGS
SACRAMENTO RT
ALL BUSES

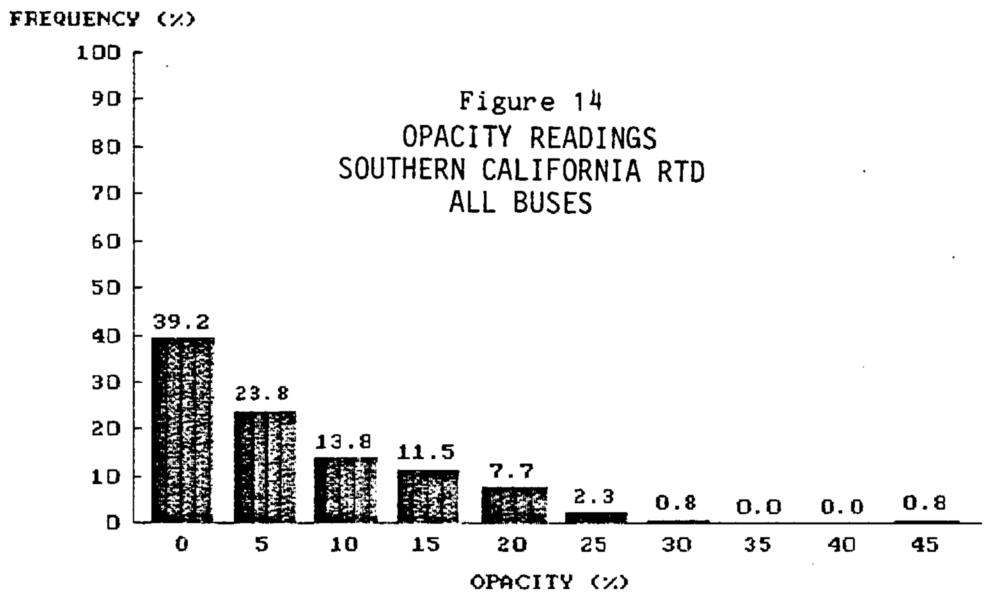


Figure 14
OPACITY READINGS
SOUTHERN CALIFORNIA RTD
ALL BUSES

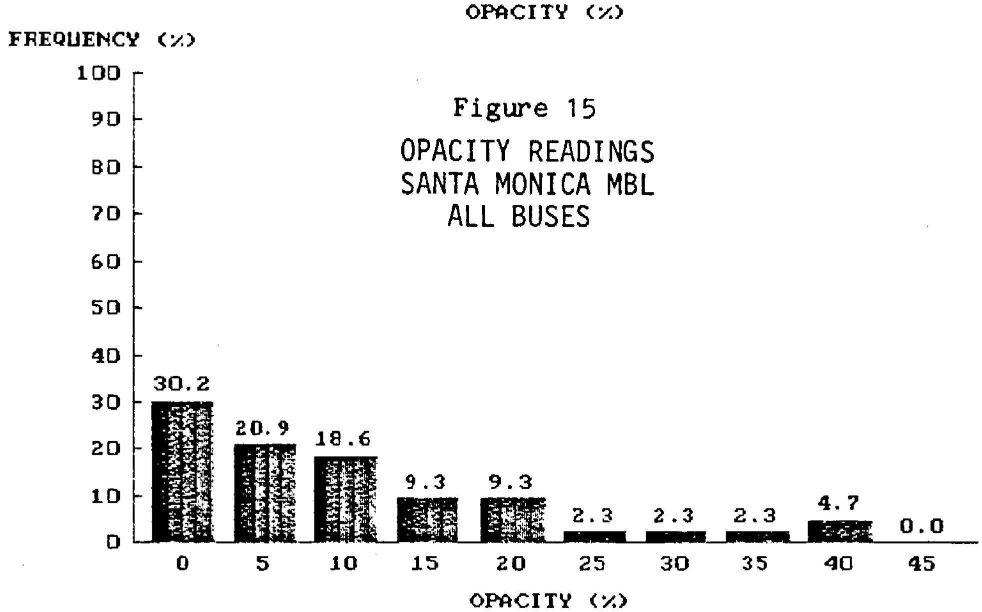


Figure 15
OPACITY READINGS
SANTA MONICA MBL
ALL BUSES

Section 6

MAINTENANCE AND FUEL PURCHASE PRACTICES

Following the Field Survey phase of the study, meetings were held with representatives of the South Coast Air Quality Management District, the California Air Resources Board, and the three transit districts that were involved in the survey. During these meetings, the scope of the study was explained, data regarding the maintenance history of buses was requested, and the routine maintenance and fuel purchase practices used by each of the transit districts were discussed.

The maintenance and fuel purchase practices used by each of the districts is described below.

The information contained in this section is generally based on information provided by representatives of the districts during meetings with them and during numerous follow-up conversations. In some cases written descriptions of the routine maintenance practices used were provided. Maintenance practices that are not related to engine performance were omitted from the description which appear below.

Southern California Rapid Transit District

RTD employs over 1200 mechanics to service its fleet of approximately 2,500 buses. Engines used in the RTD buses covered in the field survey were the 8V71, the 6V71, and the 6V92TA. The 8V71 engines ranged in model year from 1971 to 1978. The 1971-1973 models were federally certified. The 1974-1978 models were certified to meet California standards. The 6V71 engines were all federally certified 1968 models. The 6V92TA engines included 1980 and 1984 California certified models and 1982 federal engines.

A computerized system is used to keep track of each vehicle and to record its maintenance history. Reports are routinely printed which indicate which buses are due for maintenance and the individual mechanics who work on the vehicles record all maintenance performed at terminals which are located in each maintenance facility. The computer system is also used to keep track of the oil and fuel used by each vehicle.

Although the computerized data management system used by RTD is relatively sophisticated, there is little detailed information recorded regarding the specific nature of the problems that were identified and corrected during maintenance actions. The lack of detailed reporting is necessary to facilitate use of the system by a wide range of employees. The terminals used to record information regarding the work performed on each vehicle display a relatively limited "menu" of options from which a mechanic must choose. It is therefore not always possible to determine exactly what was done to a particular vehicle at a particular time.

The general maintenance philosophy employed by RTD is that "preventative maintenance" is the best approach. Vehicles are scheduled for inspections every 6,000 miles. The mileage on each vehicle is entered into the computer system during each refueling operation and the vehicle is scheduled for inspection when approximately 6,000 miles have been accumulated since the last inspection.

During the 6,000 mile checks, maximum engine speed is measured under no load and at "stall" (maximum speed with the transmission in gear and the brakes locked). Smoke-related maintenance would be performed during the 6,000 mile inspection only if obvious problems are noted.

Most smoke-related maintenance occurs during the "major inspection" that is performed every 18,000 miles. During this inspection, injector timing and rack adjustment, the throttle delay mechanism on turbocharged engines, air cleaner pressure drop, valve clearances, and blower output are all checked. The governor check, also performed at 6,000 mile intervals, is performed. Adjustments related to the fuel injection system and valve train are performed if necessary, dirty air cleaners are cleaned or replaced, and defective blowers are replaced.

RTD's practice is to use relatively long oil change intervals. Oil changes occur only every 18,000 miles. RTD indicates that this extended oil change interval is reasonable based on the results of routinely conducted oil analyses.

Unlike other districts, RTD routinely replaces Roots blowers on DDA engines before a major engine overhaul. RTD has found that the blowers will generally not last as long as the rest of the engine and therefore replaces blowers at about 100,000 miles on some engine families.

RTD does not have any routine replacement interval specified for fuel injectors. Injectors are generally not rebuilt until a major overhaul of the engine occurs. Some injectors may be replaced earlier, if the engine develops a noticeable "miss", or if smoke problems appear to be related to an injector defect.

Engine rebuilds are scheduled based on three factors: 1) results of the oil analysis, 2) oil consumption, and 3) experience with similar engines. For 71 Series engines, RTD expects about 300,000 to 350,000 miles between overhauls. For 92 Series engines, about 250,000 miles is expected; however, RTD says they do not yet have enough experience with 92 Series engines to know what the typical mileage between rebuilds will be.

Injector rebuilds and complete engine rebuilds are all done in-house. RTD estimates that the average engine will be rebuilt approximately three times before it is retired from service. (Retirement from service generally occurs when the chassis in which the engine fits is being phased out of the RTD fleet due to excessive wear and tear.)

RTD is experimenting with a chassis dynamometer procedure for evaluating the performance of vehicles. Smoke emission measurements under four modes of operation (idle, road load, lugdown, and full-power) are performed. RTD is not convinced that the routine use of chassis dynamometer testing will make sense for the whole fleet. According to RTD, the costs are high, and the variability in smoke levels appears to be relatively high for vehicles which are in the same state of tune.

RTD used to use DF1 fuel; however, DF2 is now used to reduce operating costs. RTD reports that the switch to DF2 reduced operating costs by approximately $4 million per year. RTD has also said that the cost savings associated with DF2 is 10-15 cents per gallon.

95% of the fuel purchased by RTD is supplied by Texaco. A combination of ASTM and RTD's own specifications are used to determine the acceptable level of quality. Table 3 shows the RTD fuel specifications compared to the actual specifications for the fuel that was in use during the time of our field survey.

Table 3

Fuel Used by Southern California RTD

	Specification	Actual
Cetane Number	40-45*	41.6
Distillation Range:		
initial boiling point, °F	375 min.	360
10 percent point	none	406
50 percent point	none	466
90 percent point	640 max.	580
end point	675 max.	622
Gravity, °API	none	35.5
Total Sulfur, percent	0.50**	0.44
Aromatic Hydrocarbon Content, min. percent	none	unknown
Paraffins, naphthenes, olefins, percent	none	unknown
Flashpoint, °F	125 min.	165
Viscosity, centistokes	1.9-4.1	2.2

* 43-45 cetane is required when combustion improving additives are used.

** Sulfur specification also requires compliance with mandated limits.

RTD says that it is their policy to not use fuel additives for smoke control, such as barium-based additives. RTD became disenchanted with additives after receiving a bad batch of fuel during 1981. In that year, RTD received a fuel shipment with an extraordinarily high level of barium additive. Injector fouling resulted and numerous complaints were received regarding excessive smoke emissions.

RTD recognizes that higher smoke levels are a problem with DF2 compared to DF1. However, RTD claims that the aromatics content of DF2 is lower, thereby leading to offsetting emissions benefits. (This claim is not supported by any of the literature we have reviewed on the relative aromatics content of DF1 and DF2.)

Santa Monica Municipal Bus Lines

MBL operates a fleet of only 146 buses. Engines currently in service include the 8V71, 8V71T, 6V71, and 6V92T. MBL said that the 6V92T engines in their fleet are "marine Diesels", but MBL also reported that all of their engines are California certified.

In contrast to RTD, there is no computerization of maintenance history. (The maintenance superintendent indicated that computerization is currently being considered.) Mileage intervals kept in log books are generally used to determine when maintenance is required.

MBL's practice is to change engine oil every 6,000 miles. Air cleaners and throttle delay valves are also inspected at this same interval.

A major inspection is performed every 48,000 miles or about once every year. During the major inspection, an injector is pulled and the top of the piston is observed to determine whether the spray pattern is acceptable. (The penetration depth and pattern of a DDA fuel injector leaves a lightly colored "shadow" on the piston crown that provides one indication as to whether the injector is performing properly.) Injectors are changed whenever the observation of the piston crown reveals a problem. Other elements of the 48,000 mile inspection include a governor check and adjustment if necessary, a check and adjustment of valve lash, and a check of the blower pressure. Injector timing and rack adjustment do not appear to be routine maintenance.

Complete engine rebuilds are performed only when the oil drained during a regular change indicates excessive grit or gum when rubbed between the fingers. Rebuilds are performed by MBL; however, injectors are sent out for reconditioning to a local fuel injection system rebuilder.

MBL says they have no particular problems with any of their engines. In contrast to the reports from RTD, the 6V92T engines are the least problem as far as smoke is concerned, according to MBL. (Our field survey results are not consistent with this belief.)

MBL specifies DF1 fuel meeting ASTM specifications. In addition, a minimum Cetane rating of 45 (vs. 40 under the ASTM specification) is specified. The supplier is Gasco and the refiner is Texaco. No fuel analysis was available for the fuel being used during the time of our field survey. MBL says DF1 is specified because it is a cleaner burning fuel. The maintenance superintendent says he would prefer to use JP4 (jet fuel) because it virtually eliminates all smoke.

Sacramento Regional Transit

RT operates a fleet of approximately 200 buses. RT's system for managing maintenance records is similar to RTD's in that it is highly computerized. Engines currently in service include mid-'60's 8V71's, '73-'75 model 8V71's, and '82 model 6V92T's. The 6V92T's are reported to be "truck" engines rather than coach engines. All models are reported to be California certified.

The maintenance philosophy used by RT can best be expressed by the old saying: "If it ain't broke, don't fix it." Interestingly, RT was just beginning to implement maintenance schedule revisions more consistent with this philosophy at the time that our field study was performed. The buses we observed are the last ones that will be maintained under the previous maintenance schedule that involved "tune-ups" every 100,000 to 125,000 miles.

The new maintenance schedule replaces the major tune-up with a comprehensive chassis dynamometer test of each vehicle. During the chassis dyno test, a "power curve" is run to determine whether the engine output is within 80% of that observed for new engines. Exhaust opacity will also be evaluated. At the present time (April, 1985) the opacity measurement is strictly visual. However, RT has ordered a portable smoke meter that will be routinely used in the future.

Vehicles which pass the dyno test will receive no adjustments.

The vehicles which we observed in the field were maintained under the previous schedule which included 100,000 to 125,000 mile tune-ups. The tune-up included inspection and, if necessary, adjustment of the valves, governor and injector timing and rack setting. Injector replacement was performed if the vehicle exhibited excessive smoke or power loss.

The most frequent maintenance interval used by RT, under both the old and the new maintenance schedule, is a 3,000 mile check. Each bus is first thoroughly warmed up (by driving it on the road). During the road test the vehicle is checked for proper shift speeds, excessive vibration, and other problems that would be obvious during the operation of the vehicle.

After the road test, the vehicle is brought back to the garage and, with the transmission in neutral, the maximum governed rpm of the engine is checked. The governor is adjusted on out-of-spec engines. The vehicle is also placed in gear, with the brakes applied, and the accelerator is fully depressed. (Since the vehicles are equipped with automatic transmissions, rpm is limited by the stall speed of the torque converter.) The opacity of the exhaust plume is visually checked for opacity. Maintenance is scheduled for any vehicles which exhibit "excessive" smoke levels.

The 3,000 mile check also includes a measurement of the pressure drop across the air cleaner element. Cleaning or replacement of the element is performed as necessary. The throttle delay mechanism on turbocharged engines is also checked during the 3,000 mile inspection.

Oil changes are performed during every other 3,000 mile check (i.e., at 6,000 mile intervals).

Unlike RTD, RT does not perform "preventative" maintenance on blowers. Blowers are run until failure or until the engine is overhauled. No routine inspection of blower output is included in the maintenance schedule. Blowers are rebuilt whenever they have to be removed from the vehicle for any reason.

Engine rebuilds are performed when indicated by the results of an oil analysis program combined with an assessment of engine oil consumption trends and total mileage accumulated since the last rebuild. Typical engine life before rebuild is about 250,000 miles on the 71 Series engines. RT does not yet have enough experience with 92 Series engines to know how frequently they will have to be rebuilt. RT says they are watching the engines closely as they approach 150,000 miles, since they have heard that 150,000 miles may be the average life of this engine. All rebuilds are done in-house, including injector rebuilds.

To minimize smoke levels at the lowest possible cost, RT purchases DF1 and DF2 in a 60/40 ratio. The supplier of the two fuels varies because it is RT's practice to avoid long-term contracts and purchase its fuel on the spot market. Detailed analysis of the fuel being used during the field survey was not available.

The fuel blend that is used is the result of experimentation. RT used to use DF1 exclusively, but switched to DF2 in order to reduce costs. An obvious increase in smoke levels occurred with the shift to DF2. Because RT officials believed the smoke levels with DF2 were unacceptable, blends of DF1 and DF2 were evaluated. RT officials indicated that they would prefer to use DF1 exclusively, but feel that the cost could not be justified.

Summary

Table 4 summarizes the smoke-related maintenance and fuel purchase practices of the three districts.

Table 4
Routine Maintenance Practices

	Southern California RTD	Santa Monica MBL	Sacramento RT
Governor Adjustment	check every 6,000 miles	check every 48,000 miles	check every 3,000 miles
Injector Timing & Rack Adjustment	check every 18,000 miles	check if problem reported	check every 100,000 miles*
Throttle Delay Adjustment	check every 18,000 miles	check every 6,000 miles	check every 3,000 miles
Air Cleaner	check every 18,000 miles	check every 6,000 miles	check every 3,000 miles
Valve Adjustment	check every 18,000 miles	check every 48,000 miles	check every 100,000 miles*
Blower Pressure	check every 18,000 miles	check every 48,000 miles	never checked
Oil & Filter Change	18,000 miles	6,000 miles	6,000 miles
Replace Injectors	when miss occurs	when spray pattern indicates	when smoke or power loss occurs
Rebuild ** Engine	when oil analysis or excess oil use indicates	when excess grit or gum can be felt in oil	when oil analysis or excess oil use indicates
Fuel Specification	ASTM DF2 w/ higher Cetane if additives are used	ASTM DF1 w/ 45 Cetane min.	60/40 Blend of DF1 & DF2 meeting ASTM specifications

* Immediately after our field survey, RT's maintenance schedule was changed to a check and adjustment of valve and injector settings only if the vehicle fails a chassis dynamometer test of power and exhaust opacity.

** Each district will also rebuild engines if a catastrophic failure of a major component occurs near the average time for a rebuilt or if the engine is suffering from a significant performance loss due to a loss of compression.

Section 7

DATA ANALYSIS

In order to determine possible relationships between maintenance practices, fuel quality, and observed smoke emissions, detailed vehicle descriptions, fuel analyses, and maintenance histories were requested from each of the transit districts. The information requested from each district included the following:

- Description of routine maintenance schedules for all engine systems which affect visible emissions;
- Description of any special maintenance procedures which are used when complaints are received regarding high smoke levels;
- Specifications used for fuel purchases;
- Available fuel analyses for the fuel used during the time of the field survey;
- Chassis model and model year for each bus observed in the field survey;
- Gross and curb weights of each bus;
- Transmission type for each bus;
- Engine model and model year for each vehicle including information regarding whether the engine was certified to California or federal standards;
- Total mileage accumulated on each engine;
- Mileage accumulated since last engine rebuild;
- Mileage accumulated since last routine engine maintenance;
- Mileage accumulated since last non-routine maintenance;
- Description of all non-routine maintenance performed on the engine that was smoke-related;
- Mileage accumulated since last injector change; and
- Record of any visible emission complaints for each vehicle.

Review of the initial submittal of information received from each district indicated a number of omissions and unclear descriptions of maintenance histories that were addressed through further consultation with the districts. All of the vehicle descriptions and engine-related maintenance histories from the three transit districts were stored in computerized data files with the use of a database management and reporting program. Some of the more significant data entries for each vehicle are tabulated in Appendix A.

Difference in Smoke Levels Between Turbo and Non-Turbo Engines

As indicated in Figures 16 and 17, there was a dramatic difference between the observed smoke levels for turbocharged and naturally aspirated engines. Naturally aspirated engines most frequently had invisible exhausts. As indicated in Figure 16, 85.5% of the naturally aspirated bus engines exhibited peak smoke levels of 5% or less. With the exception of one non-representative bus excluded from the sample, all of the naturally aspirated buses were below 20% opacity.

Figure 17 indicates an entirely different distribution of smoke levels for buses equipped with turbocharged engines. The most frequently occurring opacity level was 10%. The range of opacity levels went all the way from zero to 45%.

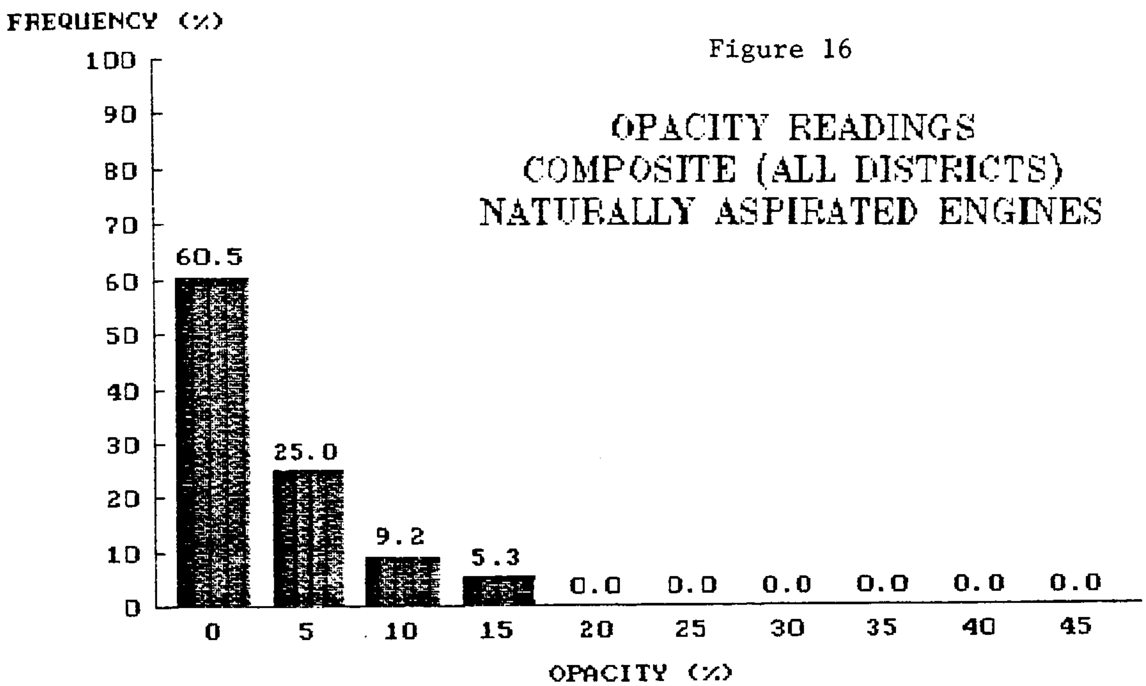
Figures 18, 19, and 20 show that there were similar distributions of opacity levels recorded for the naturally aspirated engines operated by the three different transit districts. Zero percent opacity was the most frequently occurring smoke level for each of the districts. The maximum opacity observed from naturally aspirated engine powered buses was also the same for all three districts - 15%.

Figures 21, 22, and 23 show the distributions of opacity levels for the turbocharged engines operated by each of the districts. Only Southern California RTD's buses exhibited a peak frequency of opacity at zero percent. In contrast, none of the turbocharged engines operated by Sacramento RT and Santa Monica MBL were observed to have zero percent opacity. The peak frequency of opacity level for both the Sacramento and Santa Monica turbocharged buses was 10%.

As shown in the figures, there were also differences in the range of opacity readings for the turbocharged buses from the three districts. Sacramento's turbocharged models were all within the range of 5% to 15%. Southern California RTD's turbocharged models ranged from zero to 40%. Santa Monica MBL's turbocharged models ranged from 5% to 45%.

Figure 16

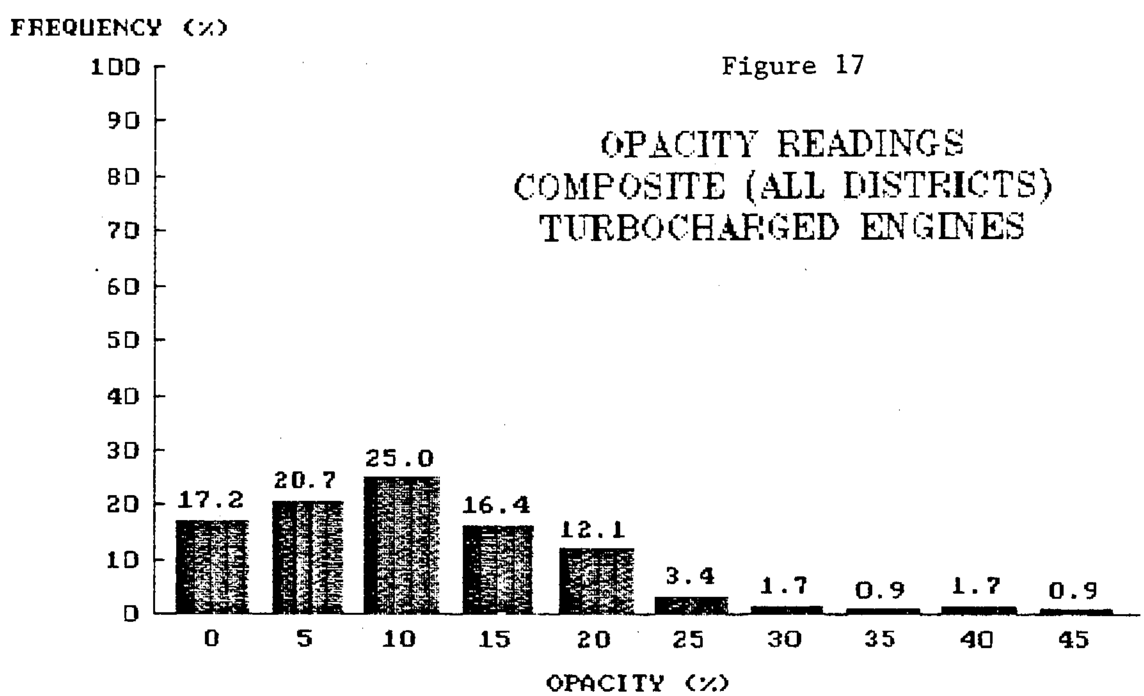
OPACITY READINGS
COMPOSITE (ALL DISTRICTS)
NATURALLY ASPIRATED ENGINES



SAMPLE SIZE = 152

Figure 17

OPACITY READINGS
COMPOSITE (ALL DISTRICTS)
TURBOCHARGED ENGINES



SAMPLE SIZE = 116

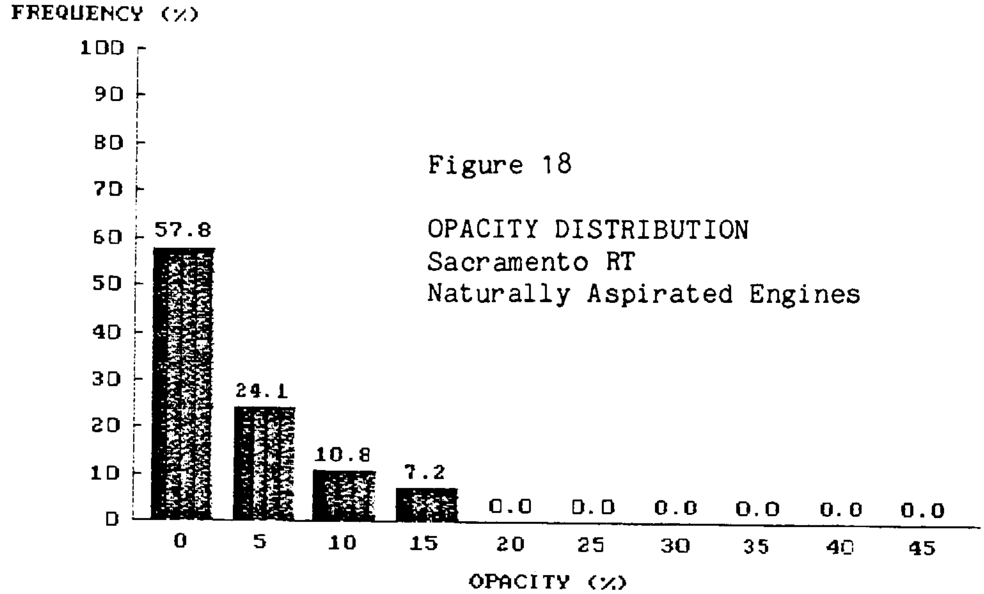


Figure 18

OPACITY DISTRIBUTION
Sacramento RT
Naturally Aspirated Engines

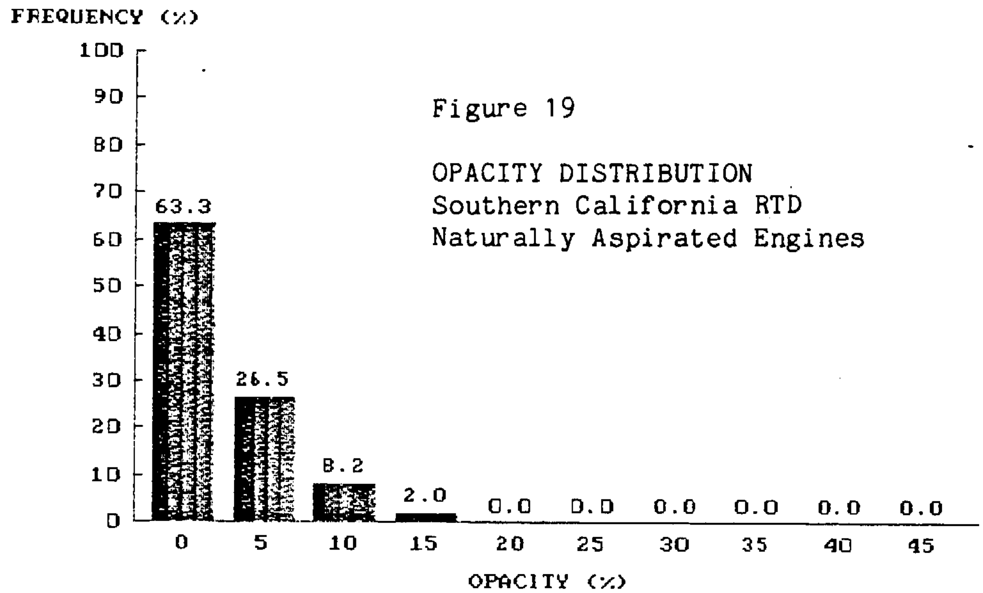


Figure 19

OPACITY DISTRIBUTION
Southern California RTD
Naturally Aspirated Engines

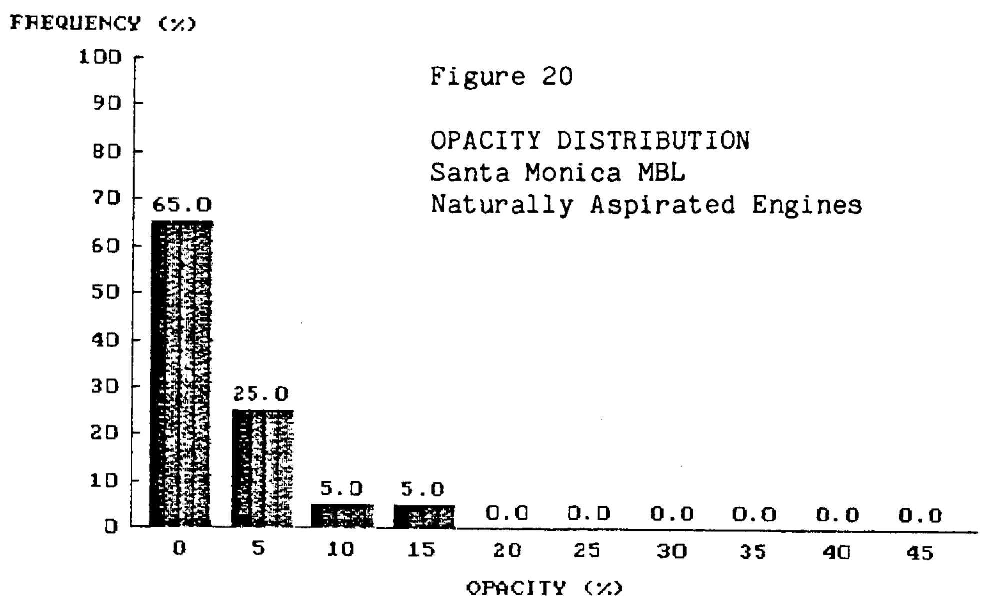


Figure 20

OPACITY DISTRIBUTION
Santa Monica MBL
Naturally Aspirated Engines

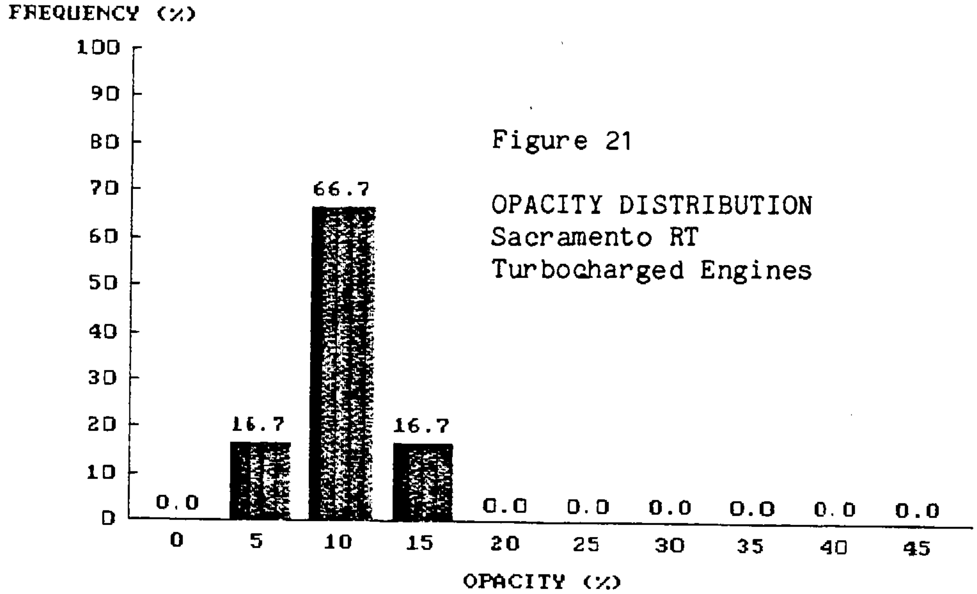


Figure 21

OPACITY DISTRIBUTION
Sacramento RT
Turbocharged Engines

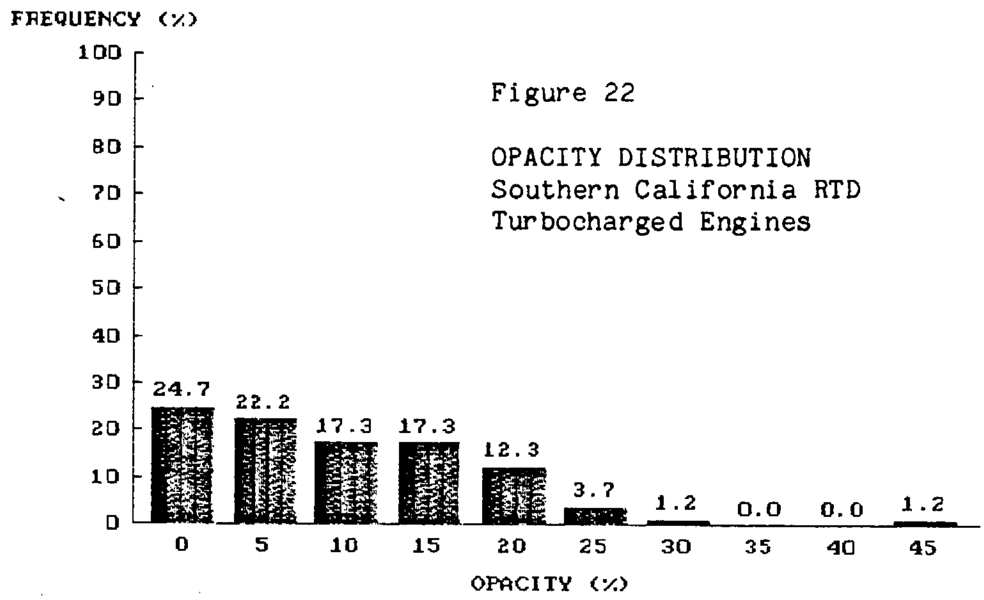


Figure 22

OPACITY DISTRIBUTION
Southern California RTD
Turbocharged Engines

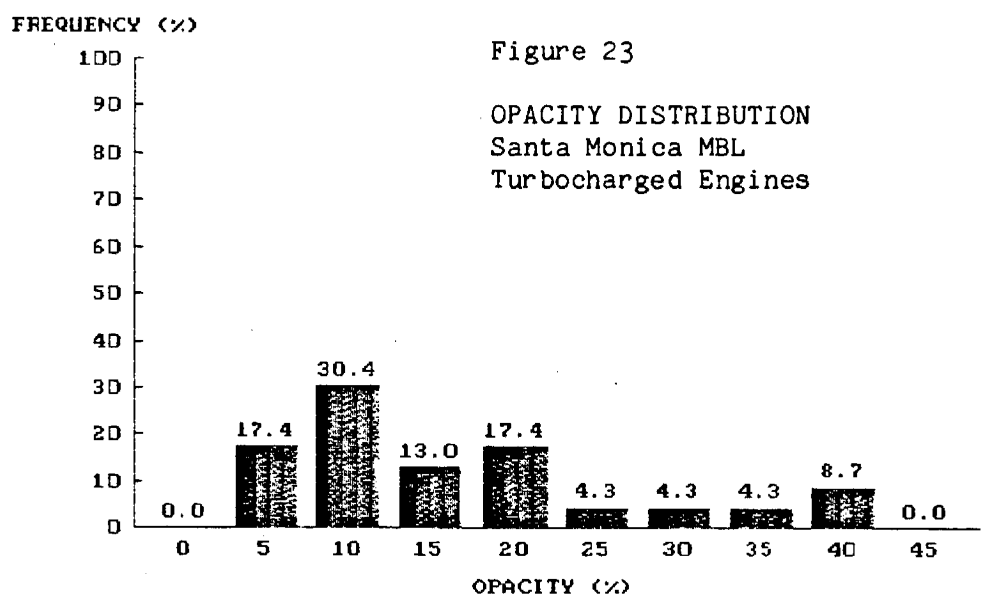


Figure 23

OPACITY DISTRIBUTION
Santa Monica MBL
Turbocharged Engines

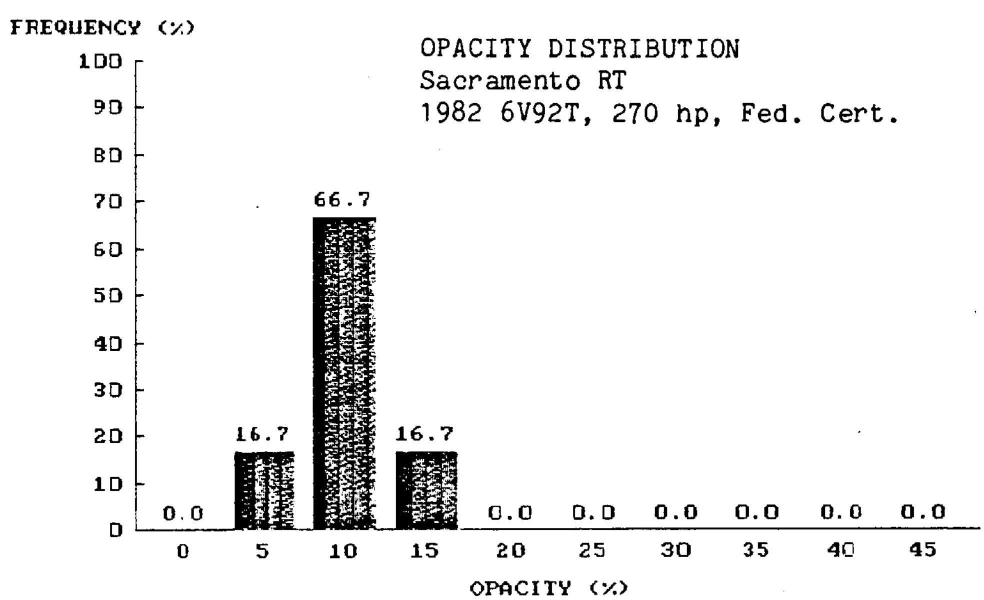
Opacity distributions for each different engine model operated by each transit district are shown in Figures 24 through 44. Note that where there are significant sample sizes, there is often a fairly wide range of observed smoke opacities. For example:

- Figures 25 and 27 indicate that 1975 and 1960's vintage 8V71N engines operated by Sacramento RT range from 0-15% in opacity;
- Figure 28 indicates that 1984 model 6V92T engines operated by Southern California RTD range from 0-15% opacity;
- Figure 30 indicates that 1980 model 6V92T engines operated by Southern California RTD range from 0-45% opacity; and
- Figures 40 and 41 indicate that 1981 model 6V92T engines and 1980 model 8V71T engines operated by Santa Monica MBL range from 5-40% opacity;

All of the engines shown in each of the figures numbered 24 through 44 are of the same horsepower rating, the same certified configuration (federal or California), and were using the same fuel at the time of the field survey. The wide range of opacity shown for some models may be an indication that there were differences in the "state of tune" of the engines that were affecting smoke levels.

Figure 24

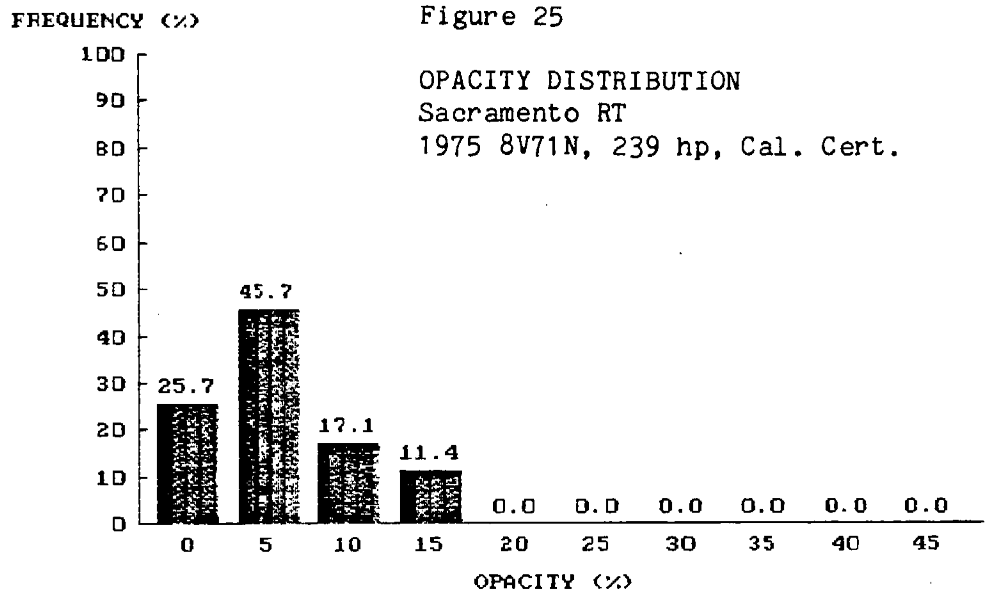
OPACITY DISTRIBUTION
Sacramento RT
1982 6V92T, 270 hp, Fed. Cert.



SAMPLE SIZE = 12

Figure 25

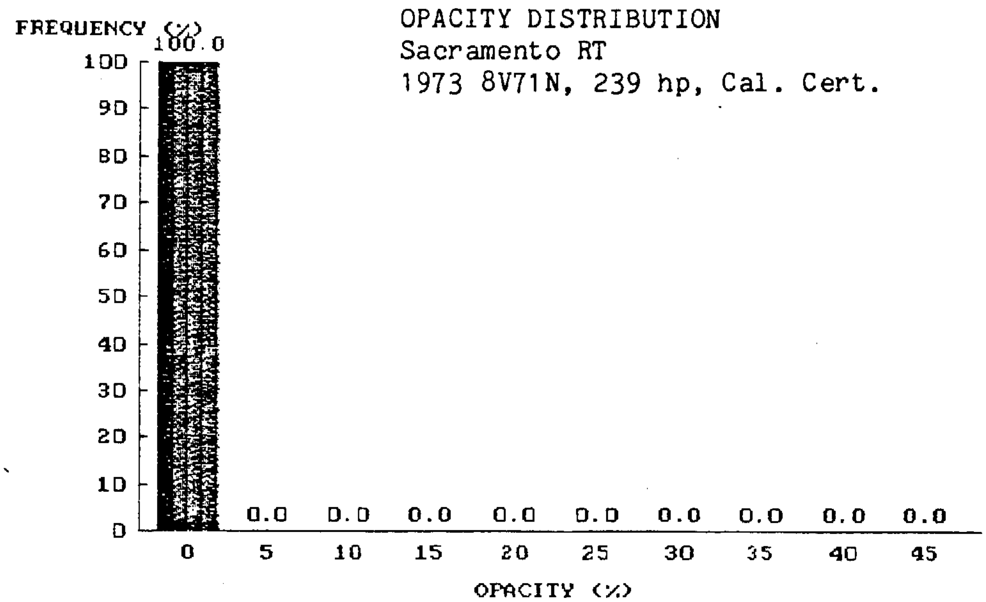
OPACITY DISTRIBUTION
Sacramento RT
1975 8V71N, 239 hp, Cal. Cert.



SAMPLE SIZE = 35

Figure 26

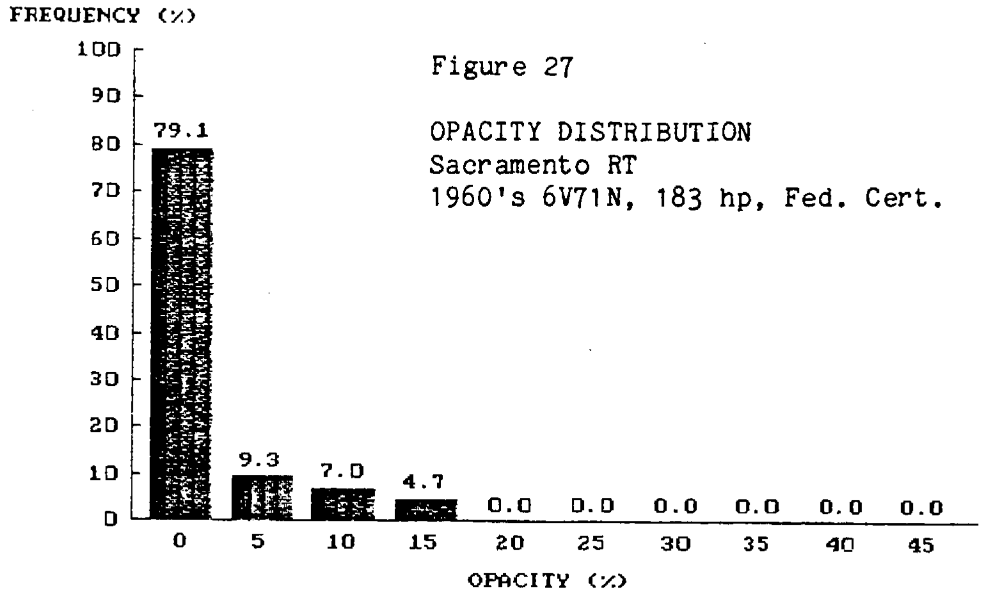
OPACITY DISTRIBUTION
Sacramento RT
1973 8V71N, 239 hp, Cal. Cert.



SAMPLE SIZE = 5

Figure 27

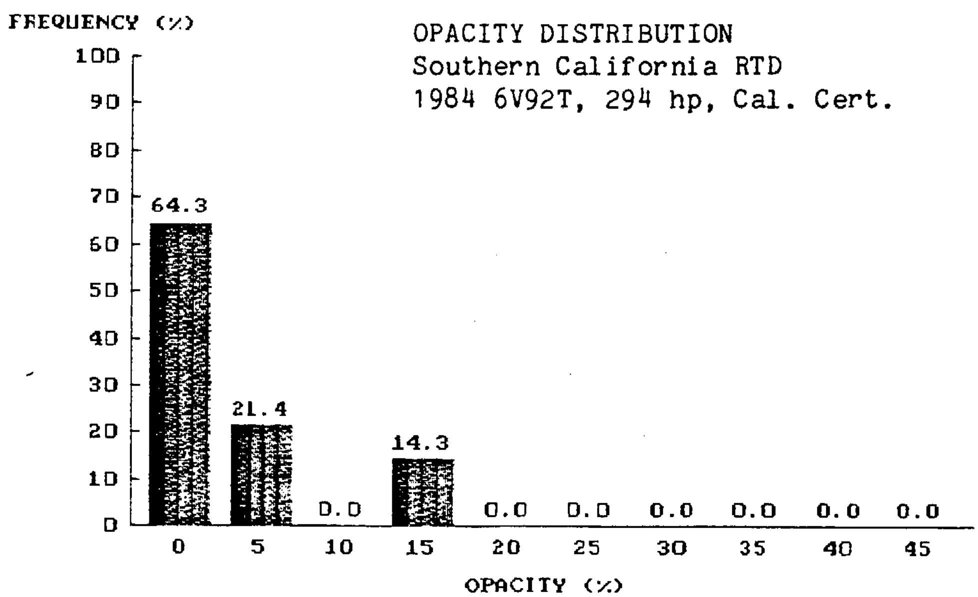
OPACITY DISTRIBUTION
Sacramento RT
1960's 6V71N, 183 hp, Fed. Cert.



SAMPLE SIZE = 43

Figure 28

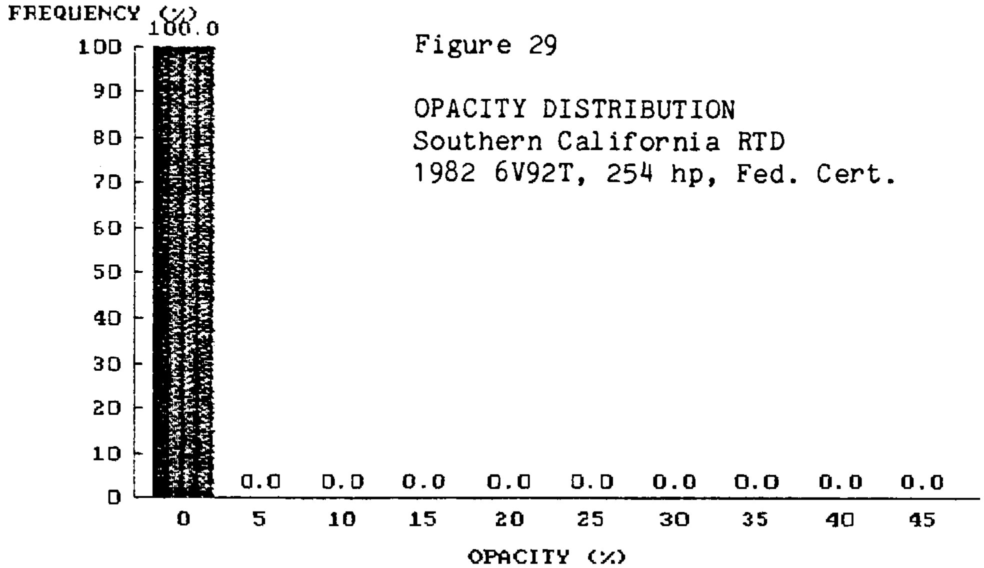
OPACITY DISTRIBUTION
Southern California RTD
1984 6V92T, 294 hp, Cal. Cert.



SAMPLE SIZE = 14

Figure 29

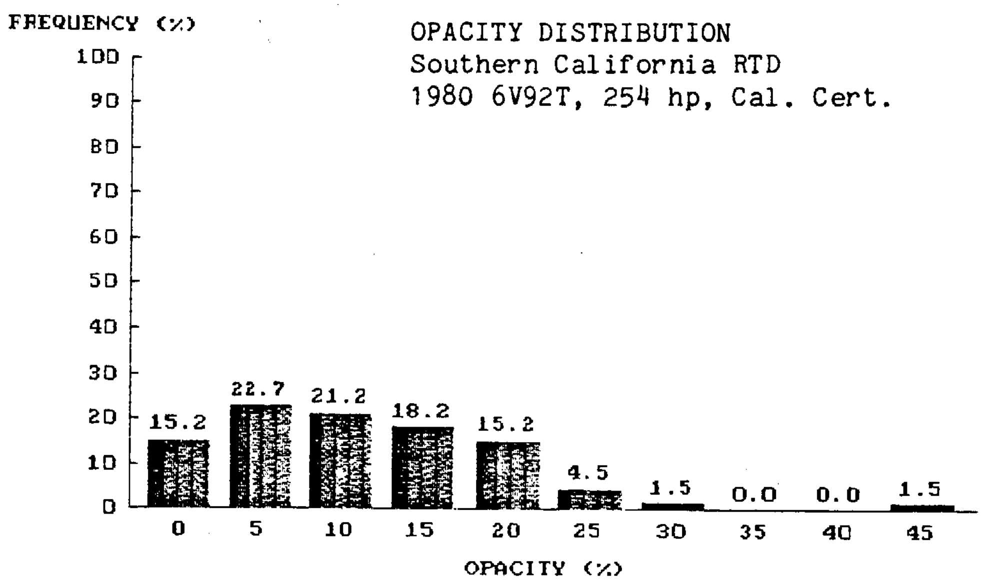
OPACITY DISTRIBUTION
Southern California RTD
1982 6V92T, 254 hp, Fed. Cert.



SAMPLE SIZE = 1

Figure 30

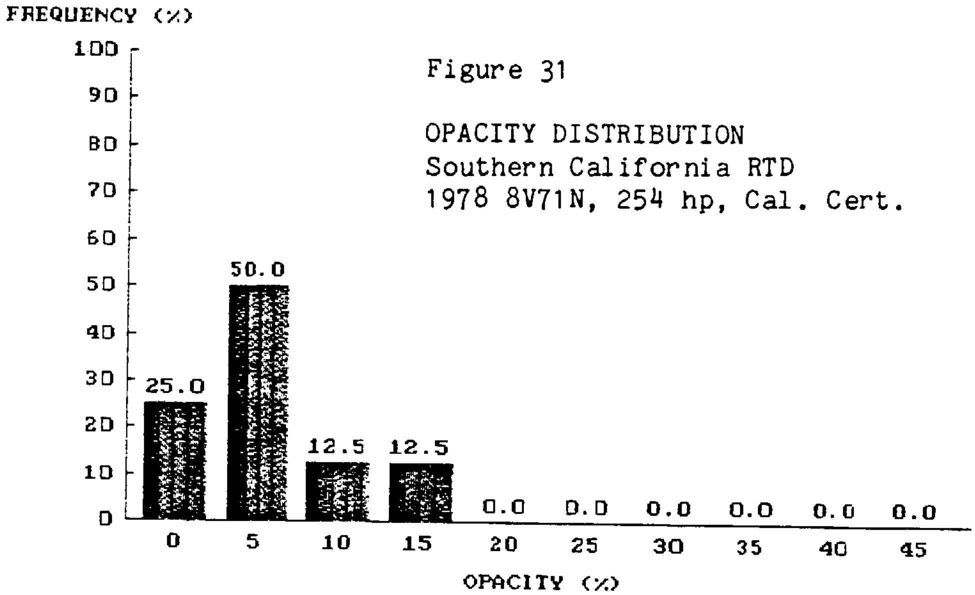
OPACITY DISTRIBUTION
Southern California RTD
1980 6V92T, 254 hp, Cal. Cert.



SAMPLE SIZE = 66

Figure 31

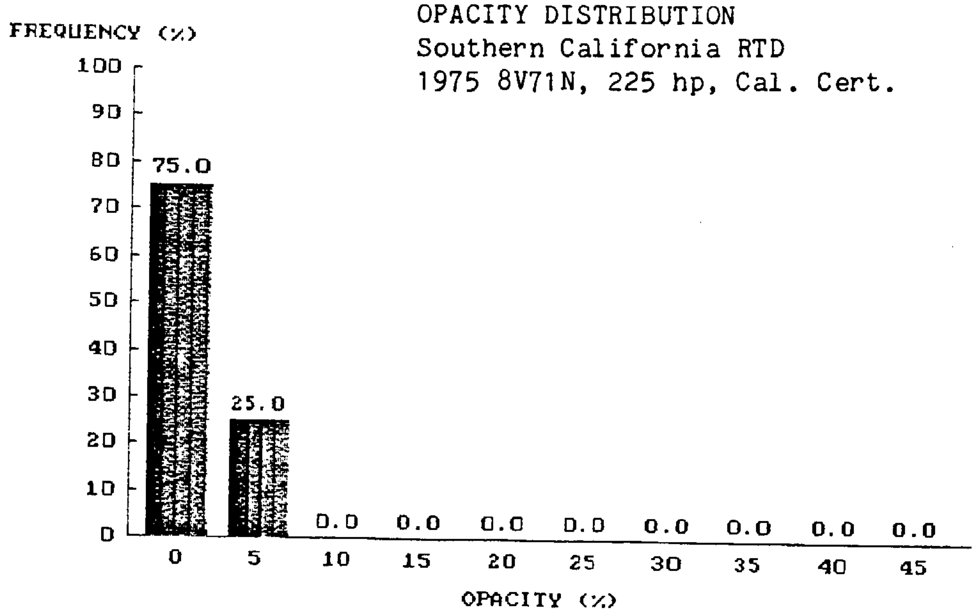
OPACITY DISTRIBUTION
Southern California RTD
1978 8V71N, 254 hp, Cal. Cert.



SAMPLE SIZE = 8

Figure 32

OPACITY DISTRIBUTION
Southern California RTD
1975 8V71N, 225 hp, Cal. Cert.



SAMPLE SIZE = 8

Figure 33

OPACITY DISTRIBUTION
Southern California RTD
1974 8V71N, 254 hp, Cal. Cert.

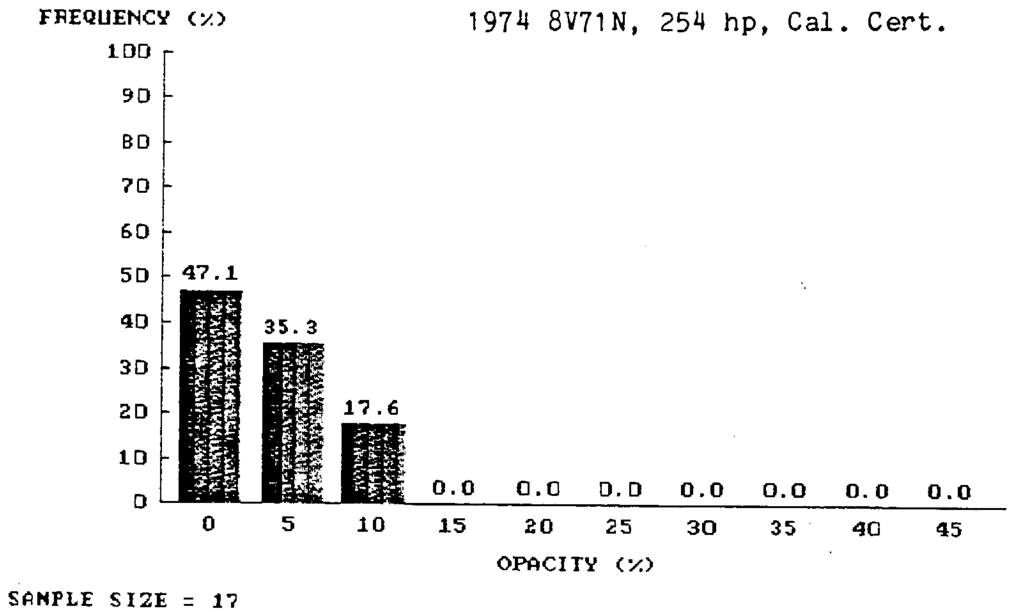


Figure 34

OPACITY DISTRIBUTION
Southern California RTD
1973 8V71N, 271 hp, Fed. Cert.

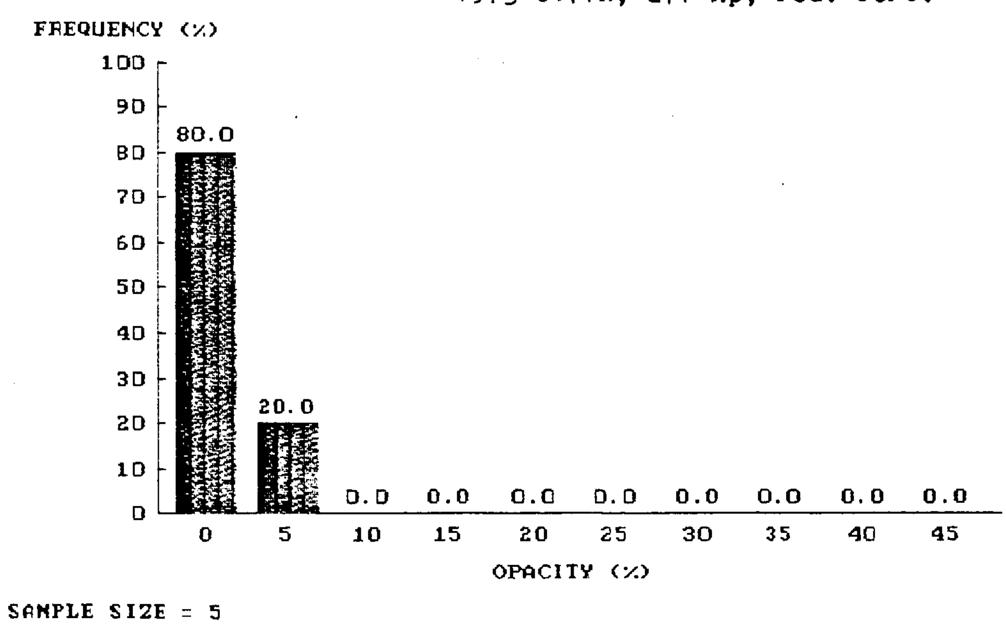
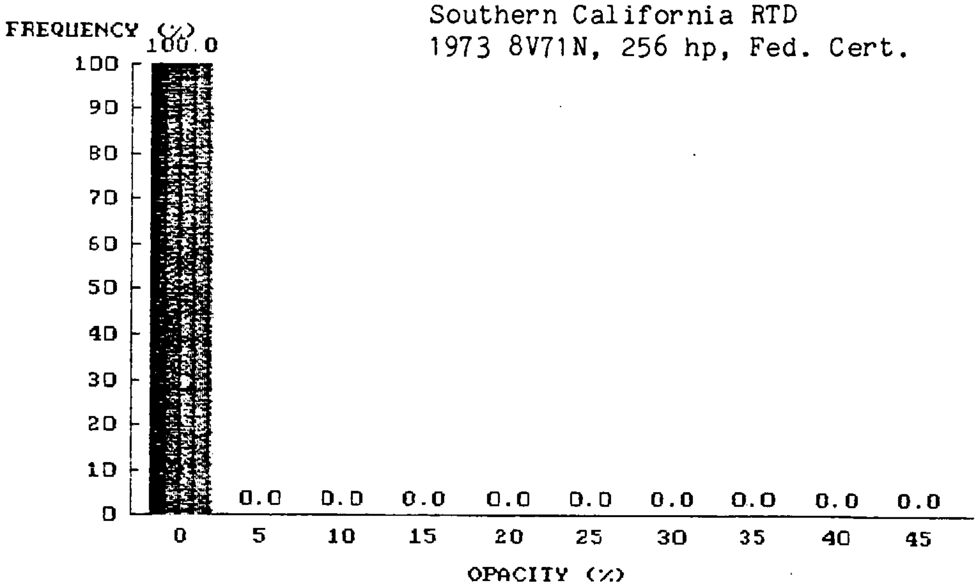


Figure 35

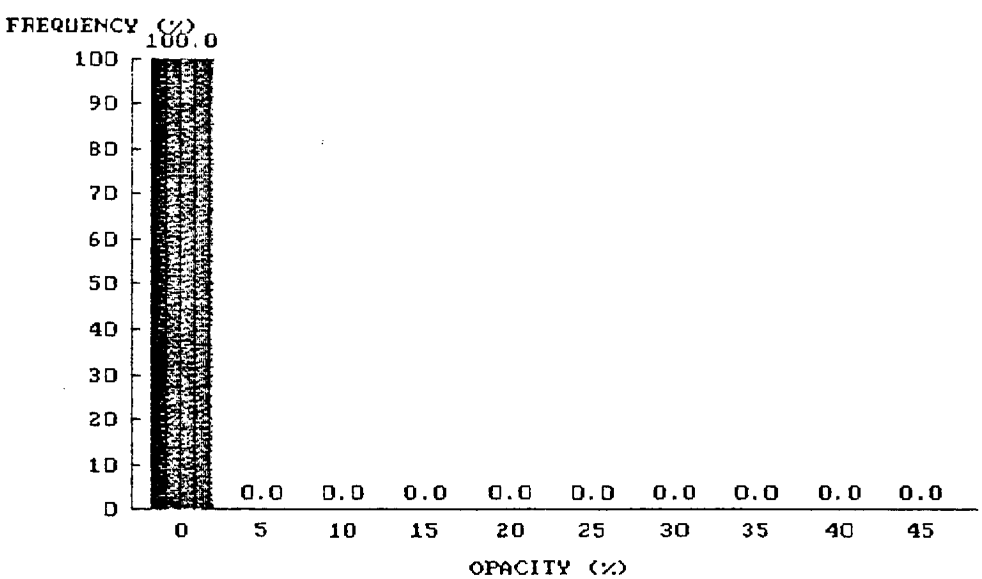
OPACITY DISTRIBUTION
Southern California RTD
1973 8V71N, 256 hp, Fed. Cert.



SAMPLE SIZE = 1

Figure 36

OPACITY DISTRIBUTION
Southern California RTD
1973 8V71N, 245 hp, Fed. Cert.



SAMPLE SIZE = 7

Figure 37

OPACITY DISTRIBUTION
Southern California RTD
1971 8V71N, 271 hp, Fed. Cert.

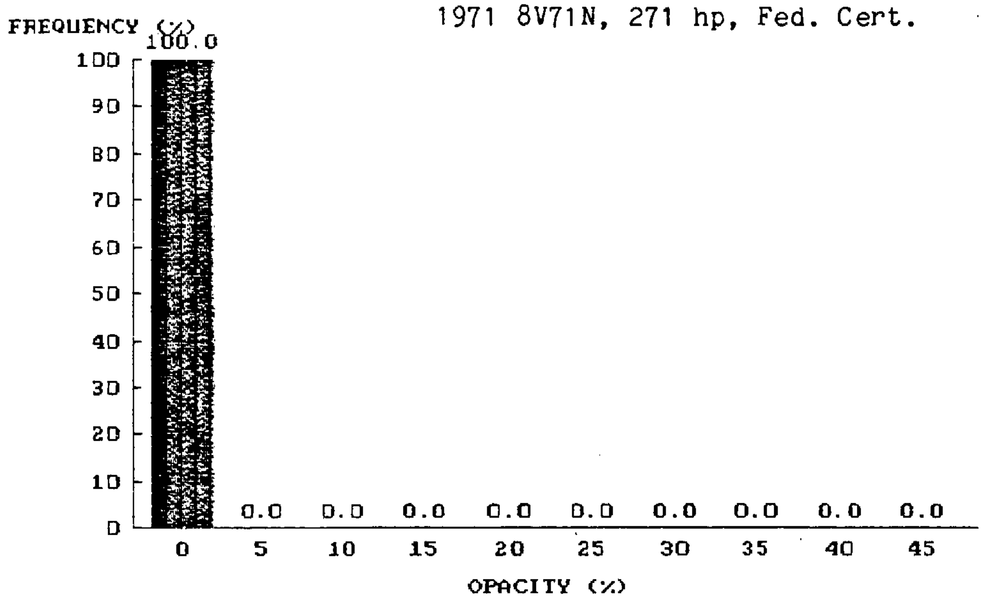
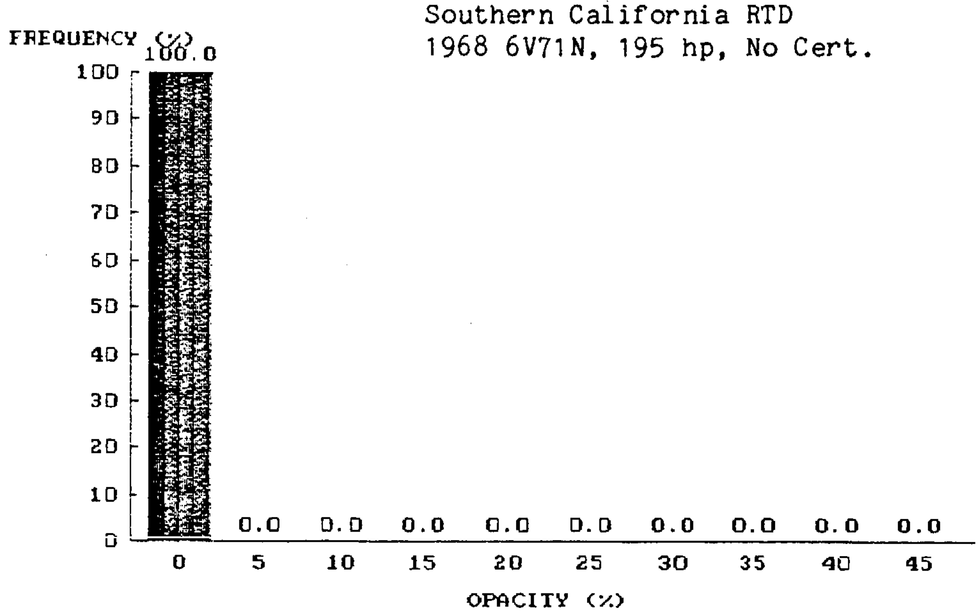


Figure 38

OPACITY DISTRIBUTION
Southern California RTD
1968 6V71N, 195 hp, No Cert.



SAMPLE SIZE = 2

Figure 39

OPACITY DISTRIBUTION
Santa Monica MBL
1982 8V71N, 318 hp, Fed. Cert.

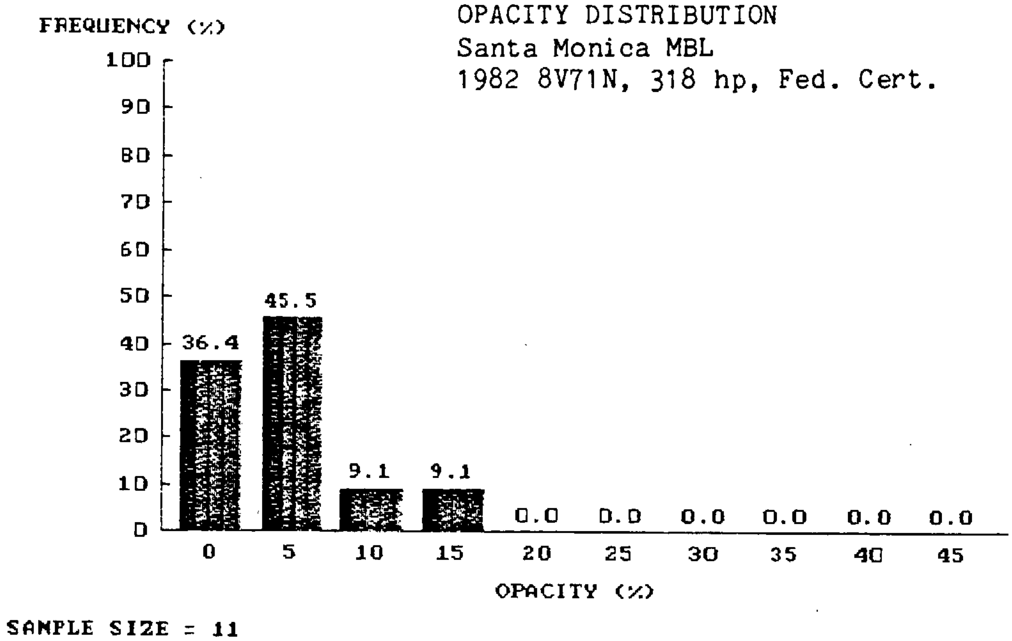


Figure 40

OPACITY DISTRIBUTION
Santa Monica MBL
1981 6V92T, 330 hp, Cal. Cert.

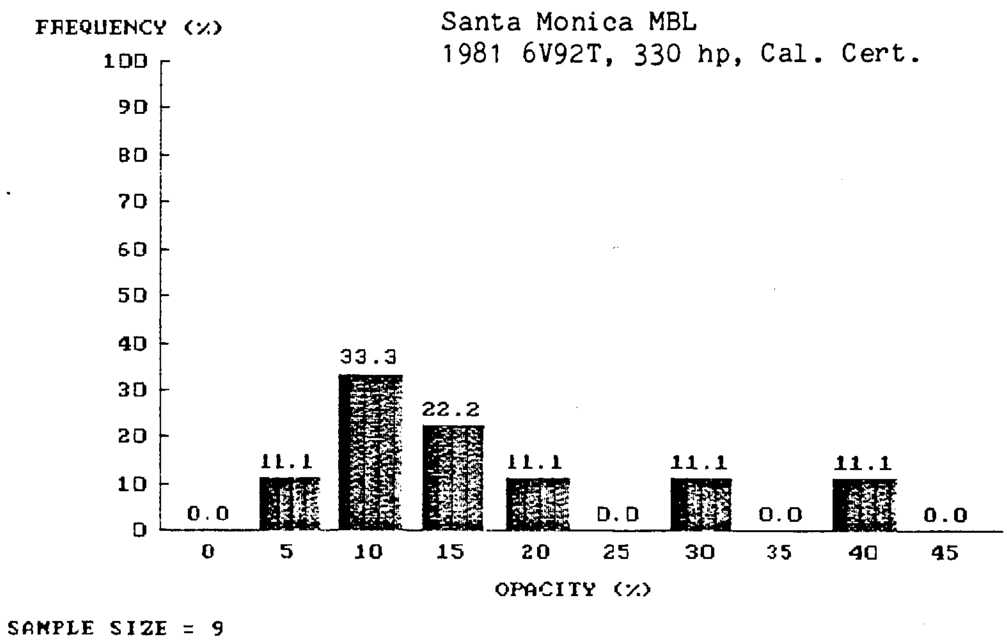


Figure 41

OPACITY DISTRIBUTION
Santa Monica MBL
1980 8V71T, 350 hp, Cal. Cert.

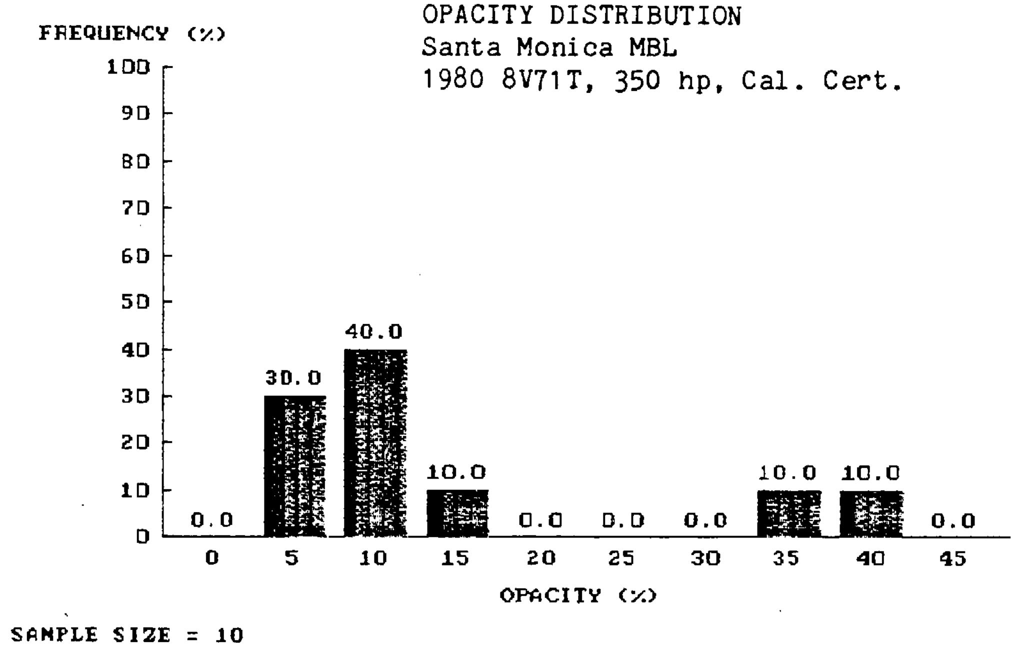


Figure 42

OPACITY DISTRIBUTION
Santa Monica MBL
1979 8V71T, 350 hp, Cal. Cert.

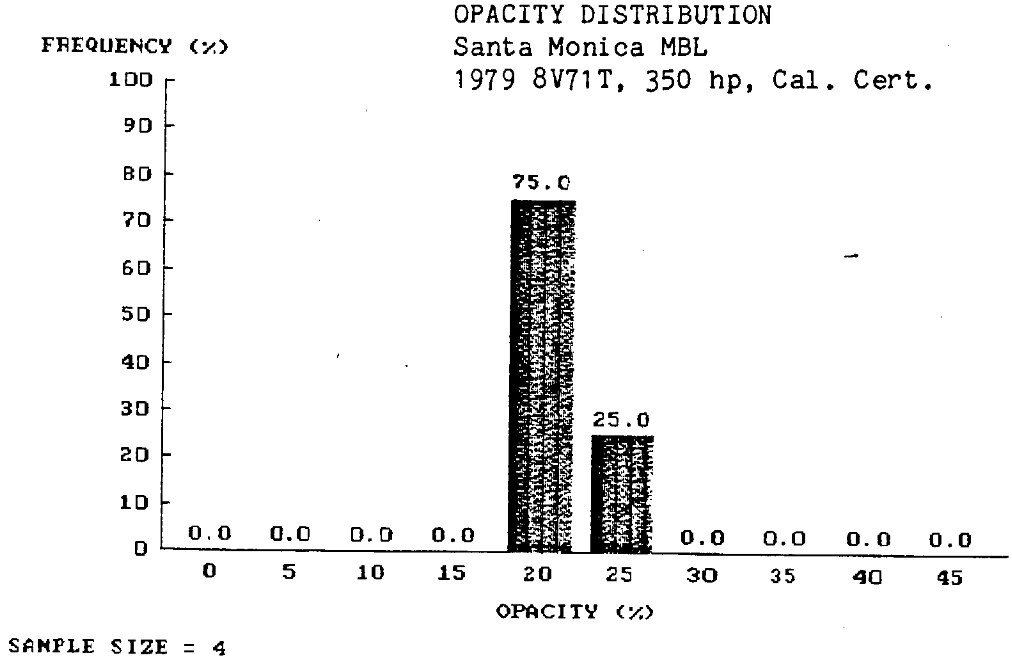


Figure 43

OPACITY DISTRIBUTION
Santa Monica MBL
1973 8V71N, 318 hp, Fed. Cert.

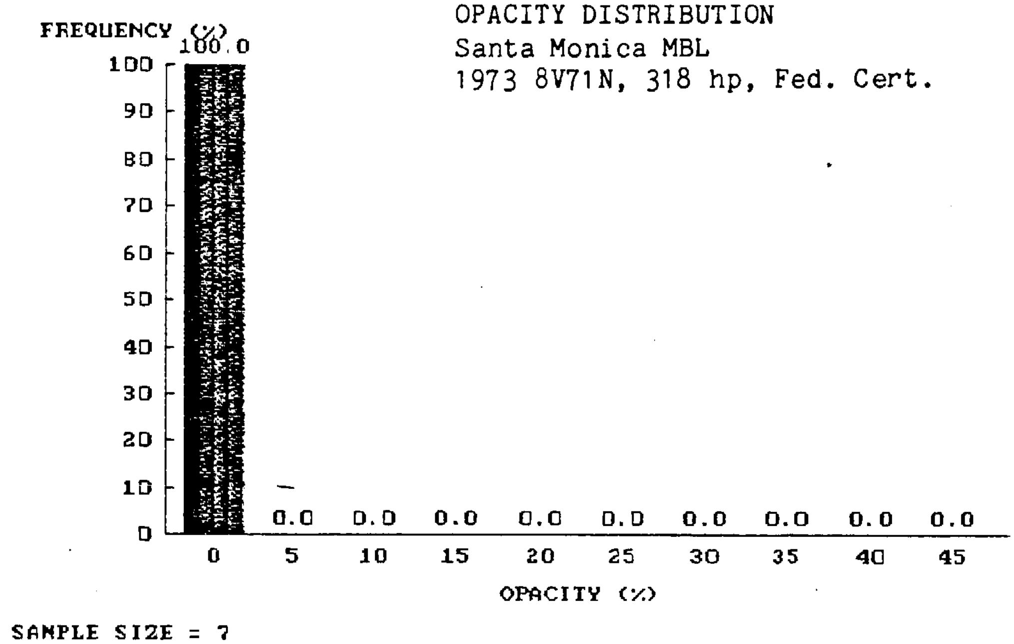
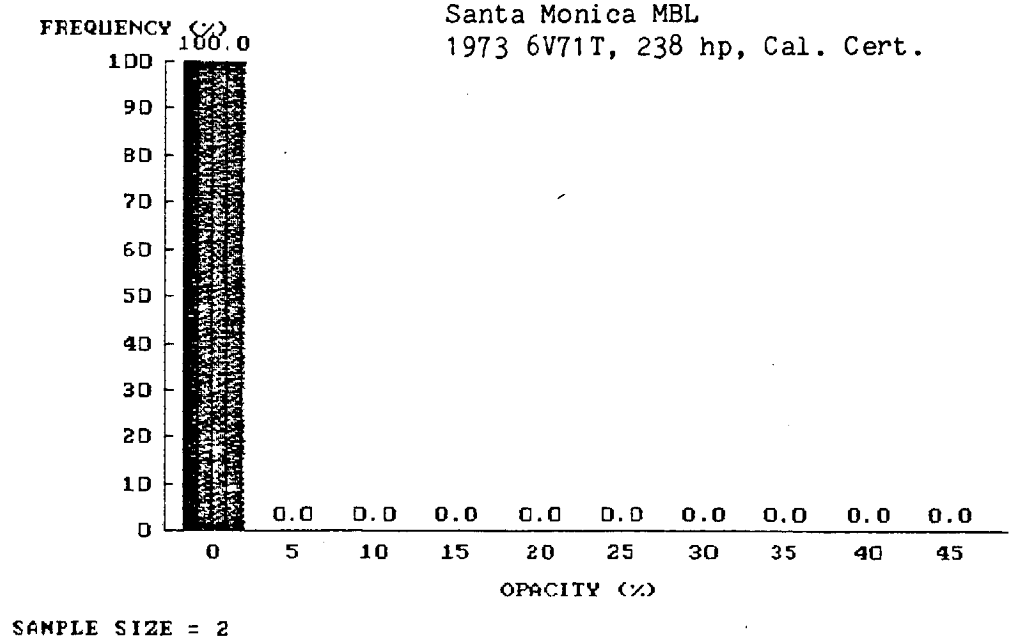


Figure 44

OPACITY DISTRIBUTION
Santa Monica MBL
1973 6V71T, 238 hp, Cal. Cert.



Analysis of Maintenance History Effects

In an attempt to determine whether the smoke levels observed from the buses covered in the field survey were related to maintenance history, regression analyses were performed.

The collective data base contained vehicles with different engine models and model years, and different certification status (federal or California). In addition to performing regressions on composite and individual district fleets, analyses of sub-fleets stratified by engine model and aspiration method were also conducted.

Linear regressions of opacity (in percent) versus both vehicle mileage since the last engine rebuild and vehicle mileage since the last injector change were determined for the composite, individual district, and individual engine models. The coefficient of determination (r^2) was computed for each of these samples in addition to the regression coefficients (intercept and slope). Using the same stratifications, additional regressions were performed between opacity and the mileage accumulated since the last smoke-related maintenance was performed on each engine.

Figures 45 and 46 show the results of the indicated relationship between mileage since rebuild and mileage since injector change for all buses in the sample. Smoke levels tended to be higher at higher mileages, as indicated by the positive slope of the least squares fit to the data. However, there was virtually no statistical significance associated with this relationship. The coefficient of determination was only 0.08 for rebuild mileage vs opacity and 0.03 for injector change mileage vs. opacity.

As shown in the two figures, a very wide range of opacities existed at all mileages. The data indicate that buses can have relatively high smoke levels immediately following a rebuild or an injector change and very low smoke levels with high mileage accumulation on both the injectors or the engine.

Because of the difference in smoke potential for different types and models of engines, it was not at all surprising that there was a poor correlation between opacity and mileage since certain smoke-related maintenance. However, further analysis of subsets of the data base didn't improve the situation.

Figures 47, 48, 49, and 50 shown the effect of separating the turbocharged engines from the naturally aspirated engines. As the figures indicate there was still a trend toward increasing smoke levels at higher mileages. However, the statistical significance of the trend remained insignificant. For the turbos, the coefficients of determination remained at 0.08 for rebuild mileage and 0.03 for injector change mileage.

Figure 45

SMOKE VS. MILEAGE SINCE LAST REBUILD
All Buses

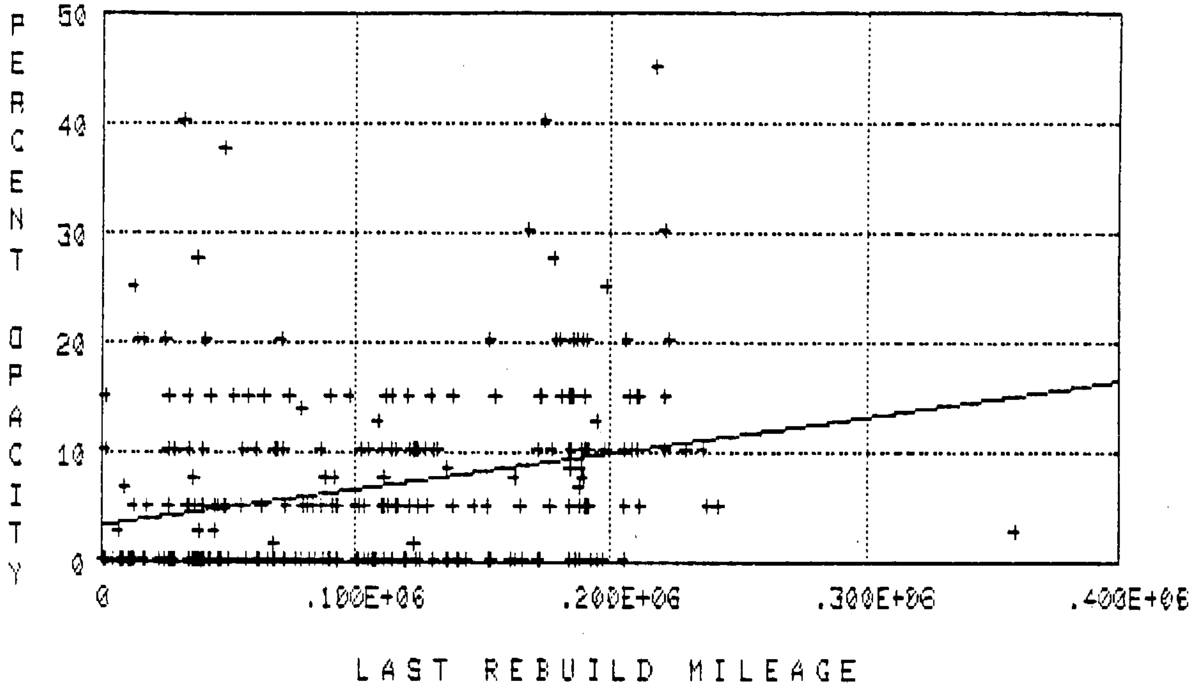


Figure 46

SMOKE VS. MILEAGE SINCE LAST INJECTOR CHANGE
All Buses

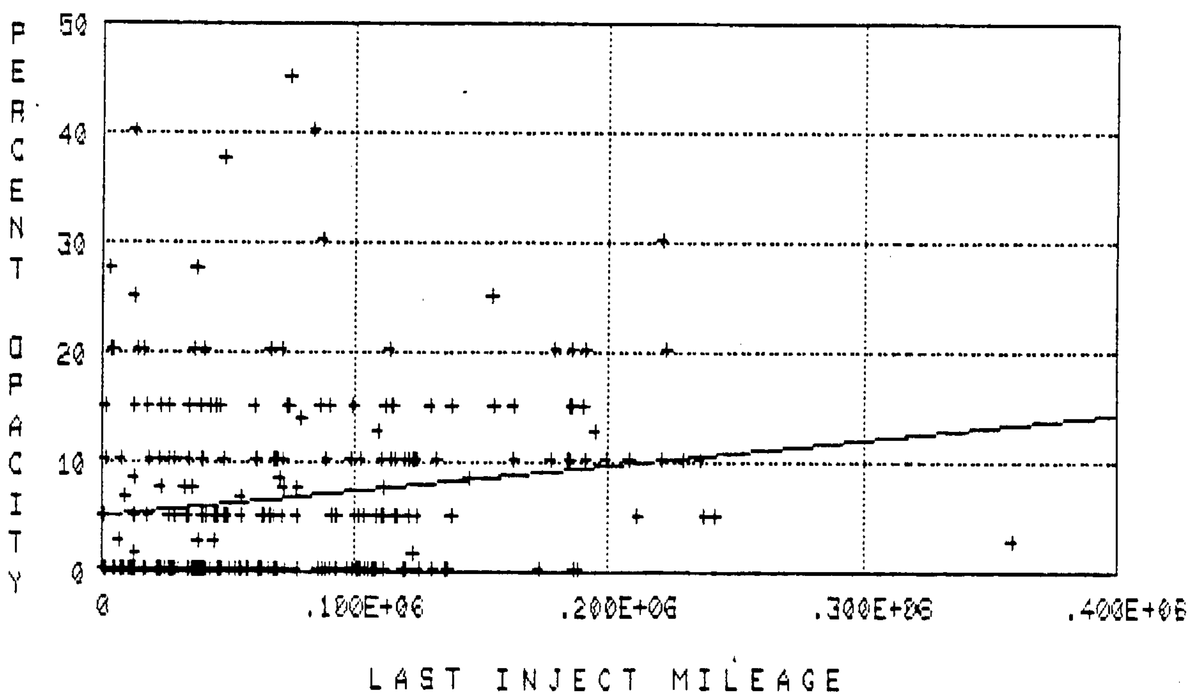


Figure 47

SMOKE VS. MILEAGE SINCE LAST REBUILD
Turbocharged Buses

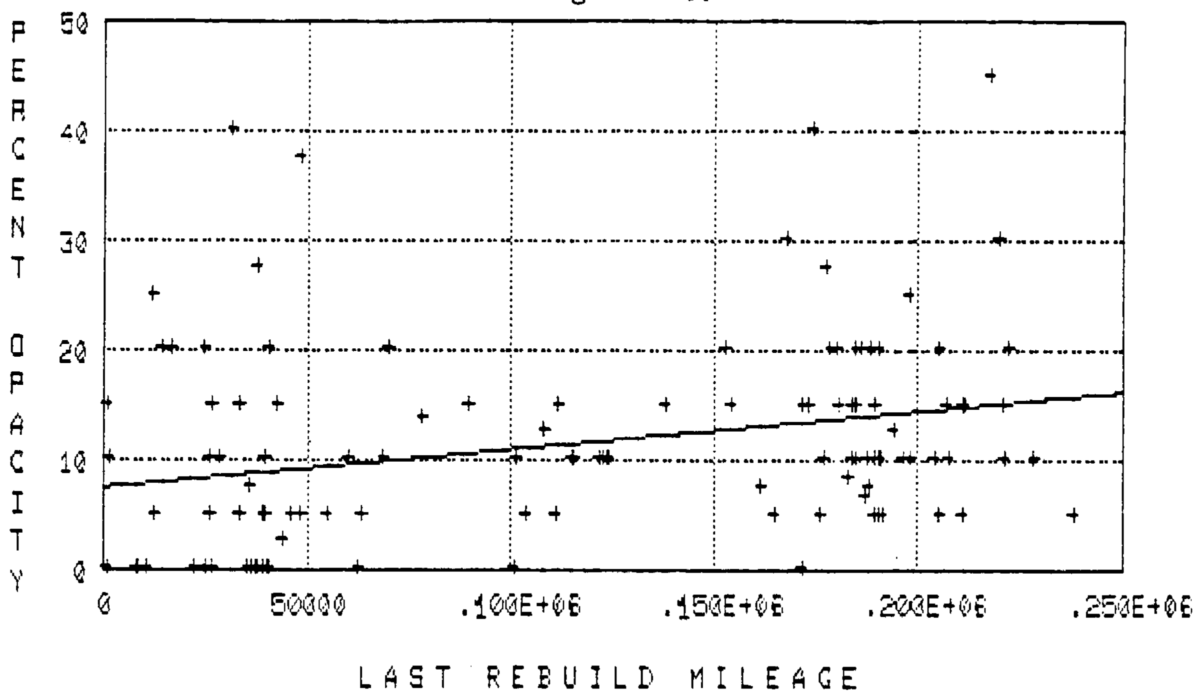


Figure 48

SMOKE VS. MILEAGE SINCE LAST INJECTOR CHANGE
Turbocharged Buses

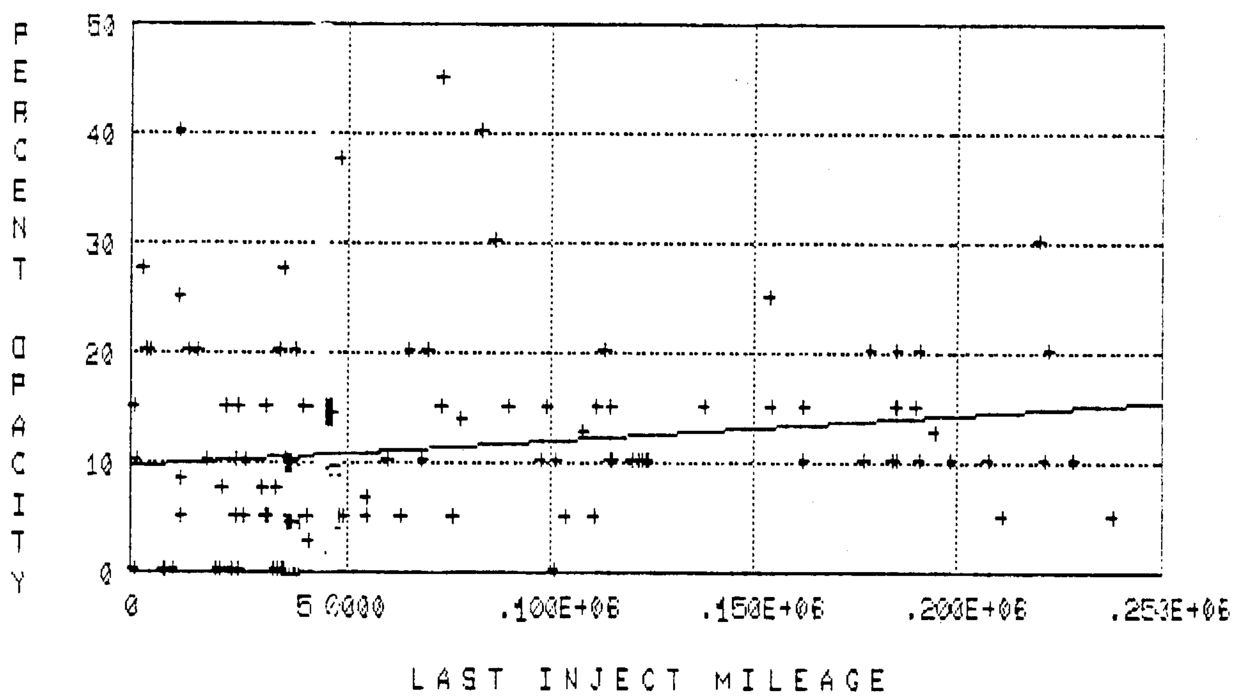


Figure 49

SMOKE VS. MILEAGE SINCE LAST REBUILD
Naturally Aspirated Buses

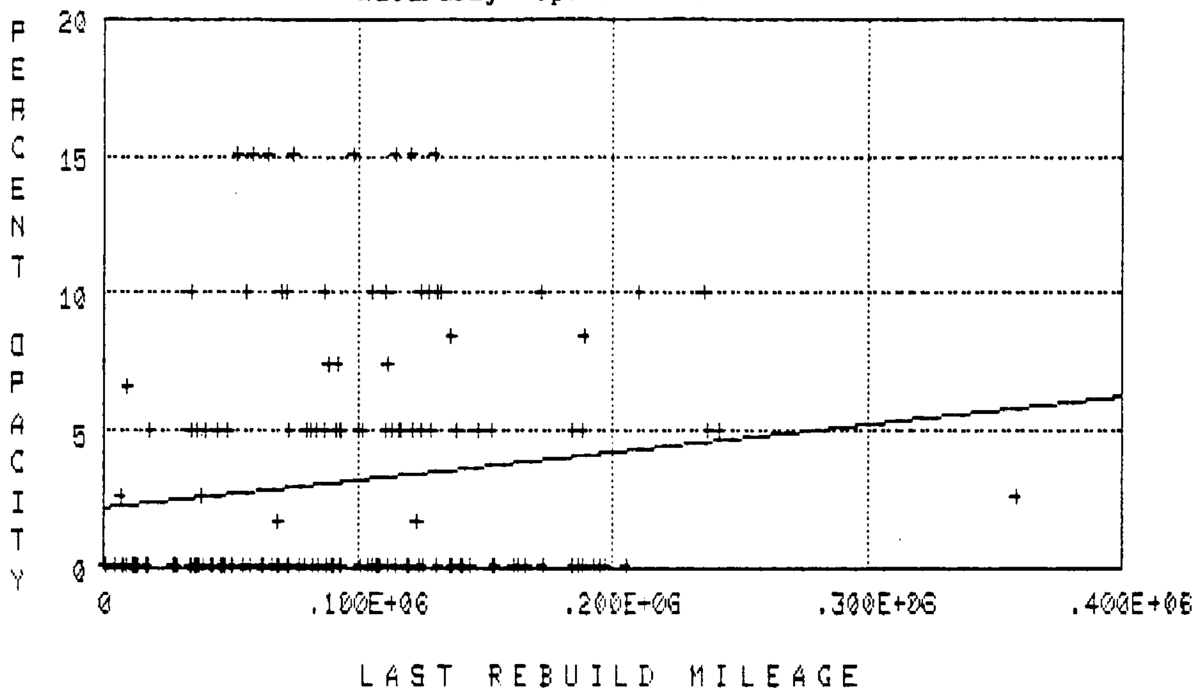
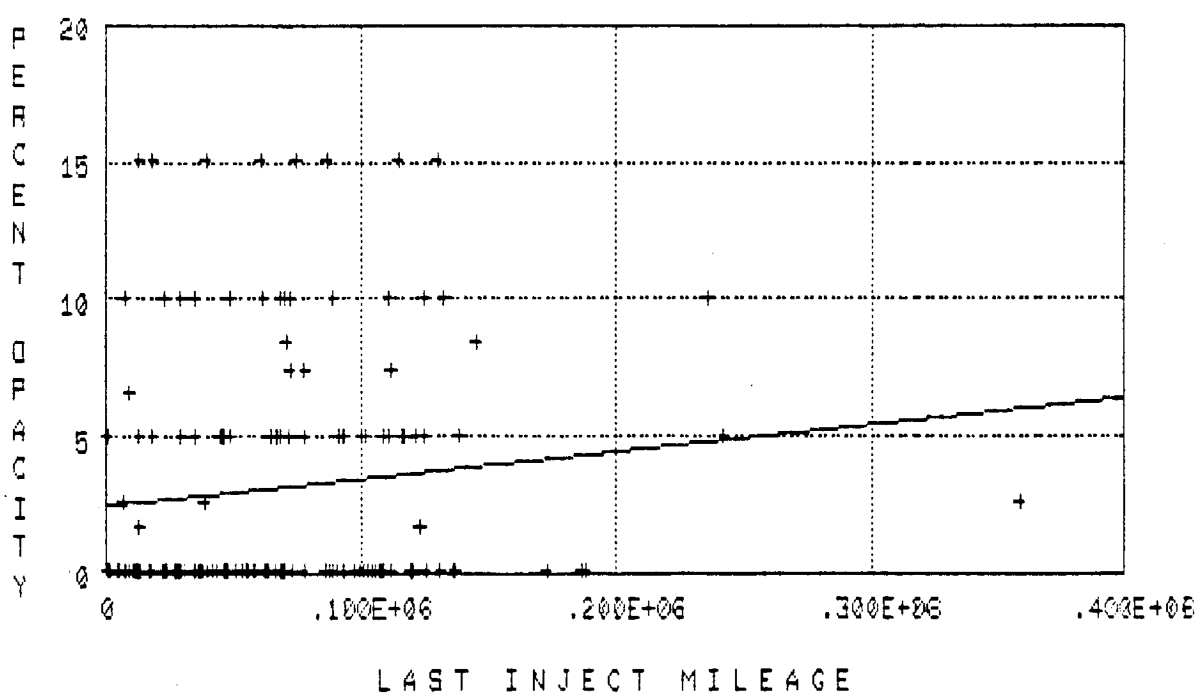


Figure 50

SMOKE VS. MILEAGE SINCE LAST INJECTOR CHANGE
Naturally Aspirated Buses



For the naturally aspirated engine powered buses, the coefficients of determination actually fell to 0.02 for rebuild mileage and 0.01 for injector change mileage.

Still further stratification of the sample also failed to demonstrate any statistically significant correlation between smoke levels and the mileage accumulated since smoke-related maintenance. Because of the possible influence of fuel differences, regressions were conducted for each individual transit district separately. We looked at all buses combined, all turbos, all naturally aspirated, and, finally, all buses within each district that used exactly the same model engine. None of these regressions showed any statistically significant relationship between smoke levels and maintenance history.

Appendix C contains the detailed results for the regressions performed.

Evaluation of Fuel Effects Was Not Possible

It was our intention to look for possible relationships between observed smoke levels and fuel specifications by comparing the observed smoke levels for nominally identical buses that were run on different fuels. However, much to our surprise, every single engine model covered by the field survey was unique to a particular district.

As shown in Table 5, the 269 buses in the survey represented twenty-one different models. Eleven of these models were unique to Southern California RTD, six were unique to Santa Monica MBL, and four were unique to Sacramento RT.

Because of this problem, all relationships between smoke and fuel quality had to based on the literature review.

Table 5

Engine Models Covered in Field Survey

Model Year	Engine Model	Certification	Horsepower	Districts with Engine
1984	6V-92T	Cal.	294	only SCRTD
1982	6V-92T	Fed.	254	only SCRTD
1980	6V-92T	Cal.	254	only SCRTD
1978	8V-71N	Cal.	254	only SCRTD
1975	8V-71N	Cal.	225	only SCRTD
1974	8V-71N	Cal.	254	only SCRTD
1973	8V-71N	Fed.	271	only SCRTD
1973	8V-71N	Fed.	256	only SCRTD
1973	8V-71N	Fed.	245	only SCRTD
1971	8V-71N	Fed.	271	only SCRTD
1968	6V-71N	Fed.	195	only SCRTD
1982	8V-71N	Fed.	318	only SMMBL
1981	6V-92T	Cal.	330	only SMMBL
1980	8V-71T	Cal.	350	only SMMBL
1979	8V-71T	Cal.	350	only SMMBL
1973	8V-71N	Fed.	318	only SMMBL
1973	6V-71N	Cal.	238	only SMMBL
1982	6V-92T	Fed.	270	only SRT
1975	8V-71N	Cal.	239	only SRT
1973	8V-71N	Cal.	239	only SRT
1960's	6V-71N	Fed.	183	only SRT

Section 8

LITERATURE REVIEW AND CONSULTATION

Fuel Quality Effects on Smoke and Particulate

Because of the limited data available on the fuel used during the field survey, and because of the presence of confounding factors (e.g., engine differences between districts), a literature review was conducted to better define the relationship between fuel quality and smoke and particulate emissions from transit buses.

Overview - There is an extensive base of literature on the effect of fuel properties on smoke and particulate emissions from Diesel engines. However, many researchers have reached conclusions regarding the significance of certain parameters which are highly questionable. Questionable conclusions arise from the fact that, in many studies, there were correlations between certain parameters that were not considered adequately. For example, in comparing two fuels with different cetane numbers, it might have been concluded that the difference in observed smoke levels was due to the difference in the cetane numbers. However, there may have been other differences between the fuels (90% boiling point, for example) that were principally responsible for the observed difference in smoke levels.

Smoke/Particulate Correlations - Much of the literature published prior to 1975 is focussed on the relationship between Diesel fuel quality and smoke levels rather than particulate emissions. These early data must be used with caution since the relationship between smoke and particulate emissions is complicated. For example, smoke levels can be reduced with the use of certain fuel additives (such as barium compounds) which do not reduce, or may even increase, particulate emissions (8). On the other hand, reductions in fuel sulfur content may reduce emitted sulfate particles, but not reduce the carbonaceous particulate that causes visible smoke (3). However, when additives are not involved, and when significant variations in sulfur levels are not occurring, there is a correlation between smoke and particulate emissions.

Shamah and Wagner (9) showed almost linear correlation between soot concentration (mg/ft^3) and Hartridge smoke numbers. A 50% reduction in visible smoke was shown to be equal to a 50% reduction in mass emissions.

Studies reported by Hare and Bradow (10) indicate that the affect of various fuels on the opacity of Diesel exhaust during the "acceleration", "lugdown", and "peak" conditions of the federal smoke test were similar to the effect on the mass emission rate of particulates over the 13-mode engine test.

Effect of Fuel Properties - Tests results reported by Hare and Bradow showed reduced smoke levels were associated with the use of DF1 compared to DF2. The combination of low sulfur content (0.04%), low aromatics content (13%), and low end point (514°F) of the DF1 fuel were significant factors. When using DF1, smoke levels from a Detroit Diesel 6V-71 engine were reduced by 37% on acceleration, 50% during lugdown, and 21% on a peak basis, compared to a "national average" DF2 fuel. The DF2 fuel used had a 0.23% sulfur content, a 639°F end point, and a 21.6% aromatics content.

Shamah and Wagner also reported smoke reductions in the range of 50% for DF1 compared to DF2. The data reported by Shamah and Wagner indicated that much of the benefit associated with DF1 is due to the "derating" effect that it has on the engine. Because DF1 is a lighter fuel, it has the effect of increasing the air/fuel ratio. By increasing an engine's fuel rate to achieve equivalent power output on DF1, Shamah and Wagner showed the effect of DF1 to be less significant. (Since vehicles in customer service are not adjusted when they change fuel grades, the maximum benefits of DF1 would be realized in the real world.)

Literature Also Reviewed by ARB - Numerous other technical papers were reviewed during the course of the study; however, the best publications for quantifying the effect of various fuel properties are several recent works that have also been reviewed by the ARB staff. These studies indicate that aromatics content, backend volatility, and sulfur content are the three most important variables related to particulate emissions from Diesel vehicles. These studies indicate that the characteristics of Diesel fuel which are associated with low particulate emissions are:

1. Low sulfur content,
2. Low aromatics content, and
3. Low 90% boiling point.

Sulfur content is principally a concern related to the "secondary" particulate pollution associated with Diesel exhaust.

In a recent staff report (4), ARB relied on the results of four studies to estimate the effects of Diesel fuel characteristics on particulate emissions. A study by Bouffard and Beltzer (5) indicated the following relationship:

$$\text{Total Particulate (gms/gal)} = 0.1424 \times (\%\ \text{off}>640°\text{F}) + 0.2326 \times (\%\ \text{aromatics}) + 4.498$$

Assuming a typical California Diesel fuel has 5% of hydrocarbons that distill off above 640°F (the average reported in a recent ARB survey), this study indicates that a reduction in aromatics content from the 33% average of current fuels would have the following effects:

Aromatics Content	Reduction in Particulate
33%	0%
25%	14%
10%	42%
5%	51%

The ARB staff report indicates that a study by Burley and Rosebrock (6) indicated the following relationship:

Particulate Index = 0.00343 x (90% boiling point)
+ 0.0102 x (% aromatics) + 0.057

Assuming a constant 90% boiling point of 611°F, the effect of changes in aromatics content would be as follows:

Aromatics Content	Reduction in Particulate
33%	0%
25%	3%
10%	10%
5%	11%

Assuming a constant aromatics content of 33%, the effect of changes in 90% boiling point would be as follows:

90% Boiling Point	Reduction in Particulate
611°F	0%
600°F	2%
550°F	8%
500°F	15%

Based on a study by Bykowski, et al. (7), the following relationship was indicated:

Particulate (mg/km) = 3.03 x (% aromatics)

+ 0.0333 x (ppm nitrogen) + 135

Assuming a constant fuel nitrogen content of 50 ppm (a typical value), the above equation predicts the following effect of changes in aromatics content:

Aromatics Content	Reduction in Particulate
33%	0%
25%	10%
10%	28%
5%	34%

The fourth study relied upon by ARB was by Chevron (3). The relationship between particulate and fuel characteristics developed by Chevron is as follows:

Particulate (gm/bhp-hr) = 0.00027 x (90% boiling point)
+ 0.00262 x (% aromatics)
+ 0.354 x (% sulfur) - 0.0402

For a 0.5% sulfur fuel with a 90% boiling point of 611°F, the relationship developed by Chevron shows the following effect of aromatics content:

Aromatics Content	Reduction in Particulate
33%	0%
25%	5%
10%	16%
5%	19%

At a constant aromatics content of 33% and a constant sulfur content of 0.5%, Chevron's analysis indicates the following effect of changes in the 90% boiling temperature:

90% Boiling Point	Reduction in Particulate
611°F	0%
600°F	1%
550°F	4%
500°F	8%

At a constant aromatics content of 33% and a constant 90% boiling temperature of 611°F, Chevron's analysis indicates the following effect of changes in fuel sulfur content:

Sulfur Content	Reduction in Particulate
0.50%	0%
0.25%	23%
0.10%	36%
0.05%	41%

Table 6 summarizes the fuel specification effects indicated by the four studies reviewed by the ARB staff.

Table 6

Summary of Fuel Effects Studied by ARB Staff

Fuel Change	----------- reference	-------------			
	Bouffard	Burley	Bykowski	Chevron	Average
Aromatics, 33% to 25%	14%	3%	10%	7%	9%
Aromatics, 33% to 10%	42%	10%	28%	21%	25%
Aromatics, 33% to 5%	51%	11%	34%	25%	30%
90% point, 611°F to 600°F	--	2%	--	1%	1%
90% point, 611°F to 550°F	--	8%	--	6%	7%
90% point, 611°F to 500°F	--	15%	--	10%	13%
Sulfur, 0.23% to 0.10%	--	--	--	16%	16%
Sulfur, 0.23% to 0.05%	--	--	--	22%	22%
Sulfur, 0.23% to 0.01%	--	--	--	27%	27%
Nitrogen, 390 ppm to 50	--	--	5%	--	5%
Nitrogen, 390 ppm to 0	—	—	5%	—	5%

Using the average of the relationships between fuel characteristics and emissions investigated by the ARB staff, directly emitted particulate reductions were calculated for the South Coast Air Basin for six hypothetical fuel specifications. The results are shown in Table 7.

Table 7

Estimated 1990 Emission Reductions
for Six Diesel Fuel Specifications
(South Coast Air Shed)

Sulfur Limit, wt%	0.05%	(0.23%)	(0.01%)	(0.12%)	(0.01%)	(0.01%)
Aromatics, vol%	--	25	10	25	10	5
90% Point, F	--	600	600	500	500	500
Directly Emitted Particulate Reduction	16% 4.4tpd	11% 3.1tpd	33% 9.2tpd	21% 5.8tpd	40% 11.1tpd	46% 12.8tpd
Sulfur Dioxide Reduction	11.8% 17.1tpd	0.0% 0.0tpd	15.9% 23.0tpd	9.5% 13.7tpd	15.9% 23.0tpd	15.9% 23.0tpd
Direct Plus Secondary Part. Reduction	21.5tpd	3.1tpd	32.2tpd	19.5tpd	34.1tpd	35.8tpd

The ARB staff estimated the cost effectiveness of the six alternative Diesel fuel specifications based on refiner's responses to a questionnaire. The refiner's provided ARB with estimates of capital costs and operating costs associated with meeting each of the six specifications. ARB accepted these estimates at face value and used them to compute the annualized cost under each alternative. In amortizing the capital investment costs over a sixteen year period, ARB used a capital charge factor of 0.267 (i.e. 26.7% of the capital investment was charged to the cost of compliance each year). Over the assumed sixteen year life of the capital facilities, 427% of the original capital investment was charged to the cost of compliance. The justification for this high capital charge factor was that the refiners were assumed to have otherwise been able to make a 15% after tax return on the capital investment. The tax rate assumed was the 46% maximum corporate tax rate.

The cost effectiveness calculation methodology used by the ARB staff appears to be very conservative. ARB's methodology does not consider the fact that the depreciation of the capital equipment needed to comply would have reduced refiner's tax burdens. In addition, the assumed profit that refiners would otherwise make from an alternative use of capital is substantial, and the calculation assumes that all refiners pay taxes at the maximum corporate average rate, which is not the case.

We believe it is also very significant that the cost-effectiveness estimates calculated by ARB were based on industry-wide compliance. The individual cost estimates provided by some refiners were much lower than the average. This is shown in Table 8 for one of the possible fuel specification scenarios that had relatively high effectiveness, but relatively low cost.

Table 8

Estimated Cost of Improving Diesel Fuel Quality
to 10% Maximum Aromatics and 600°F Maximum 90% Boiling Point

Refiner	Capital Cost $/barrel	Operating Cost $/barrel	Total Cost $/barrel
A	10.61	5.00	15.61
B	3.19	3.73	6.92
C	2.00	2.15	4.15
D	5.13	1.59	7.70?
E	3.17	1.90	5.07
F	1.40	1.24	2.64
G	3.66	2.30	5.96
H	2.19	5.96	8.15
I	--	--	--
J	7.40	2.10	9.50
L	4.75	1.88	6.63
Weighted Average	4.24	2.40	6.64
Minimum Cost Refiner	1.40	1.24	2.64
Highest Cost Refiner	10.61	5.00	15.61

As shown in the table, there was a 6:1 range in the costs estimated by the various refiners reporting to ARB. In addition, the cost estimated by one refiner was only 39.8% of the average cost for all refiners. This extreme variation in cost estimates between refiners would seem to indicate that the cost-effectiveness of providing a more limited quantity of higher quality Diesel fuel would be much lower than the estimate made by the ARB staff for compliance by all refiners.

ARB staff has estimated that uniform compliance with a 10% aromatics content, 600°F 90% point requirement would be $18.20/lb. of directly emitted (smoke related) particulate emission control in the South Coast Air Basin. Based on the range of estimates provided, it appears that this cost could drop to $7.24/lb., or even lower, if only transit bus fuel were required to comply.

Based on total fine particle reductions (including sulfate formed in the atmosphere from SO_2 emissions), the ARB staff estimated that the cost-effectiveness of a 10% aromatics limit in combination with a 600°F 90% boiling point limit would drop to $4.55/lb. In lower volumes, this cost could drop to under $2.00. (Whether this lower cost-effectiveness value should apply to Southern California transit district fuel depends on whether the transit districts continue to purchase fuel from large refiners who are subject the 0.05% sulfur limitation that applies in the South Coast Air Shed.)

Diesel Fuel Quality Trends - The concern which engine manufacturers have regarding Diesel fuel quality is typified in a preface to a Society of Automotive Engineers Special Publication (11) on the subject:

> "The availability of high-quality fuel for diesel vehicles has been, and will continue to be, important. In past years, the factors involved (crude oil properties, refinery practices, fuel demand, etc.) have been such that diesel fuel quality has been more than adequate. Today, however, and perhaps even more so in the future, the crude sources available are not as well-suited to the production of high cetane number, low cloud point diesel fuel, which burns cleanly in the combustion chamber. Because of the need for wider distribution of diesel fuel to meet the growing demand, fuel cleanliness problems have also become more prevalent.
>
> It is vital to the future success of the diesel engine that high-quality diesel fuels be available."

The concern over the deteriorating quality of Diesel fuels, and the reasons for the deterioration, have also been expressed (11) by a representative of a major fuel additive manufacturer:

> "In the past few years, there have been significant downward trends in diesel fuel quality. A major influence has been the increasing use of heavier crude oils. To achieve the desired product yield from a barrel of crude, it has been necessary to employ more catalytically cracked stocks. The effect on #2 diesel quality has been:
>
> - Increased final boiling point
> - Reduced fuel stability
> - Lower cetane number
> - Poorer cold flow properties
> - Tendency for higher exhaust particulates"

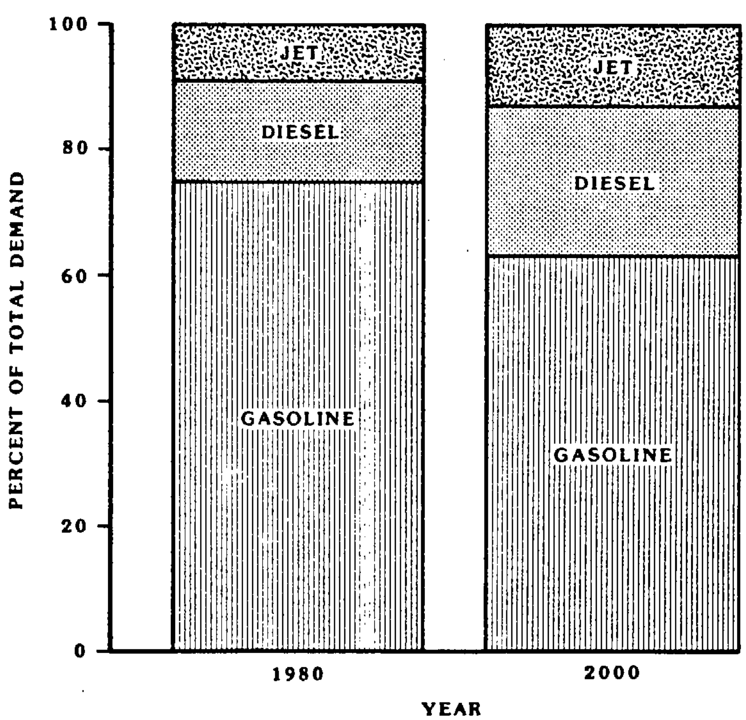
In addition to the concern over the deteriorating quality of crude oils, refiners have stated (11) that increases in the relative demand for Diesel fuel and Jet fuel will have a significant influence:

> "A problem with this increasing diesel fuel demand is that the amount of the virgin kerosene material in the crude is limited, and jet fuel demand is rising. Consequently, there is going to be less kerosene available to blend into diesel fuel in the future and both cetane and cold flow properties will suffer. Straight-run diesel has excellent cetane, but relatively poor cold flow properties and the amount of virgin material in the crude is also limited. Furthermore, the quality of this straight-run material is generally declining in cetane because the highly naphthenic crudes now being processed at many refineries produce lower cetane straight-run diesel fuel. Because of future shortages of straight-run diesel and lower quality crudes, cetane quality is expected to decline. Catalytically-cracked diesel has low cetane and fair cloud point. The good news is that it's readily available and we don't foresee problems in making sufficient volumes of it. The bad news is that cetane quality will further decline because of the poor cetane of that cat crack component."

Figure 51 shows a projection by Amoco of how the relative fractions of transportation fuels are expected to shift to less gasoline and more diesel and jet fuel by the year 2000.

Figure 51

U. S. TRANSPORTATION FUEL DEMAND



Conoco has also concluded (11) that the changing nature of Diesel fuel quality is related to the increasing demand for unleaded gasoline:

> "If you look at the big picture, the problem concerns what the refiner must do to meet the demand for high-octane, unleaded gasoline. We should never forget that the deeper we crack into the barrel, the less high-quality virgin distillate we have available from that barrel to turn into high-quality diesel fuel. That means more aromatics will flow back into the diesel fuel whether we like it or not. We're cracking deeper and deeper into the barrel.
>
> ...There is another concurrent demand out there called jet fuel that just eats our lunch when it comes to taking the heart cut of that distillate pool."

Figure 52 and Figure 53 indicates the trend in Diesel fuel quality based on two important parameters. As shown in Figure 52, the average cetane value of Diesel #2 has dropped from slightly over 50 in 1960 to about 44 in 1983. As shown in Figure 53, the average 90% boiling point temperature has increased from 560°F to almost 600°F during this same period.

Many refiner's position on the adoption of regulations to improve the quality of Diesel fuel was summarized by a representative of Gulf of Canada (11) at a recent meeting of the Society of Automotive Engineers:

> "If, as the speaker from Colorado mentioned, there was legislative action to force certain quality into the system, there would be an extremely high cost to the user. It would be politically undesirable. I am sure it would show up the next time there was an election.
>
> Overall, it may be much more cost effective to do substantial modifications to equipment (engines), to make it more flexible and more able to handle a wide range of fuels, than it is to try to push up the poor quality of the fuel."

Maintenance Effects on Diesel Smoke

One of the few references in the literature to the effect of maintenance practices on smoke, was found in a paper on the results of a study of Diesel engine retrofit kits sponsored by EPA (12). In this paper, Southwest Research Institute recommended adjustment on the fuel injection rack on DDA engines every six months. As noted in the paper, wear causes the DDA system to retard injection timing, thereby increasing smoke levels.

Figure 52

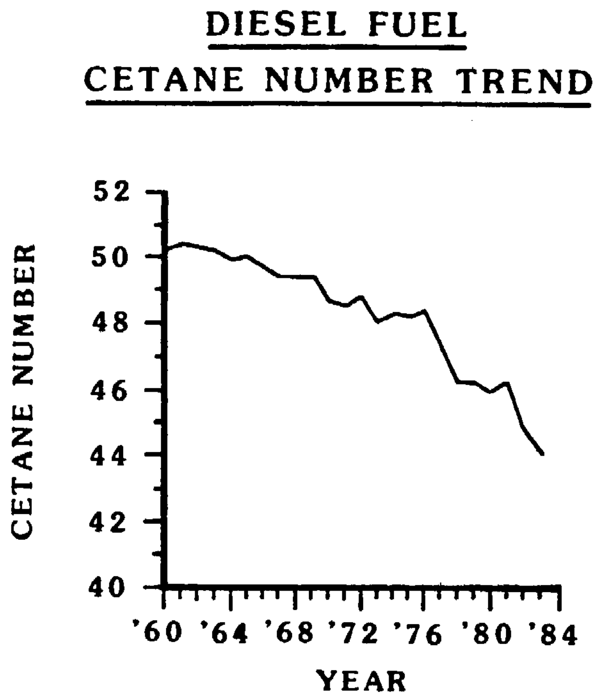
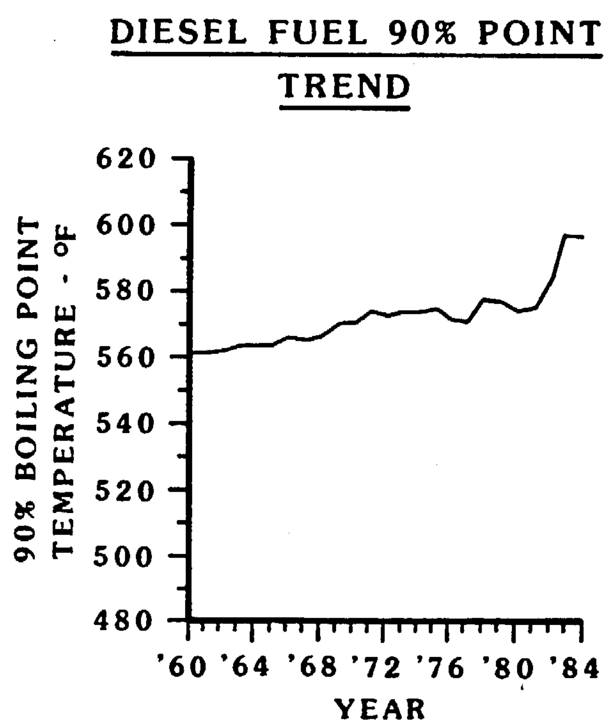


Figure 53



Section 9

Prospects for Reducing Smoke and Particulates

Maintenance Practices

Based on the analyses conducted, it does not appear that any particular maintenance schedule is associated with low smoke emissions from transit bus engines. Many engines continue to demonstrate low smoke levels with very high mileage between maintenance. However, even low mileage engines can have high smoke levels if they are not properly adjusted. It therefore appears that the most effective means of ensuring that transit buses receive adequate smoke-related maintenance would be for routine smoke inspections to be incorporated into standard maintenance procedures.

All three districts we evaluated already consider smoke levels in determining whether an engine is in need of maintenance. However, the criteria currently used do not necessarily represent the minimum feasible emission levels for each bus.

Southern California RTD apparently uses Ringelmann 1 (20% opacity) as an indicator of whether a vehicle has a smoke problem or not. Based on our field survey, most vehicles appear to be capable of doing significantly better than this if they are properly maintained and adjusted. Santa Monica MBL and Sacramento RT appear to rely on the subjective evaluations of maintenance personnel as to whether a vehicle has excessive smoke.

Although a variety of techniques could be used to incorporate routine smoke checks, observation of buses accelerating from a standing start over a 100 meter distance by a trained observer would be totally adequate for identifying problem buses. Smoke meters and expensive chassis dynamometers are not required.

Based on the results of the literature survey and the field observations, it appears that every model of bus observed can have peak emissions below 20% opacity when not in need of maintenance. Buses powered by naturally aspirated engines could comply with a requirement for peak smoke levels to be below 10%.

As shown in Table 9, more than half of the engine models operated by RTD, MBL, and RT already meet these criteria. For engines that do not already comply, the performance of other identical engines or very similar engines indicates that compliance is possible.

Table 9

Percent of Engines Not Currently Below
10% Opacity (Naturally Aspirated)
and 20% Opacity (Turbocharged)

Model Year	Engine Model	Certification	HP	District	Engines Not Below 10% (NA) or 20% (turbo)
1984	6V-92T	Cal.	294	SCRTD	0%
1982	6V-92T	Fed.	254	SCRTD	0%
1980	6V-92T	Cal.	254	SCRTD	23%
1978	8V-71N	Cal.	254	SCRTD	25%
1975	8V-71N	Cal.	225	SCRTD	0%
1974	8V-71N	Cal.	254	SCRTD	18%
1973	8V-71N	Fed.	271	SCRTD	0%
1973	8V-71N	Fed.	256	SCRTD	0%
1973	8V-71N	Fed.	245	SCRTD	0%
1971	8V-71N	Fed.	271	SCRTD	0%
1968	6V-71N	Fed.	195	SCRTD	0%
1982	8V-71N	Fed.	318	SMMBL	18%
1981	6V-92T	Cal.	330	SMMBL	33%
1980	8V-71T	Cal.	350	SMMBL	20%
1979	8V-71T	Cal.	350	SMMBL	100%
1973	8V-71N	Fed.	318	SMMBL	0%
1973	6V-71N	Cal.	238	SMMBL	0%
1982	6V-92T	Fed.	270	SRT	0%
1975	8V-71N	Cal.	239	SRT	29%
1973	8V-71N	Cal.	239	SRT	0%
1960's	6V-71N	Fed.	183	SRT	12%

With a requirement that buses be immediately scheduled for maintenance when their exhaust opacity is equal to or greater than 10% (naturally aspirated engines) or 20% (turbocharged engines), the nuisance of smoky buses could be substantially reduced. In addition, it is estimated that average smoke and particulate emissions from transit buses could be reduced by approximately 35%. This estimate was made based on the following facts:

- If the 14.5% of naturally aspirated buses currently at 10% or higher opacity could be adjusted or repaired so that they have emissions equal to the other 85.5% of the buses, average smoke emissions would be reduced from 3% opacity to 1.5%.

- If the 20.7% of turbocharged buses currently at 20% or higher opacity could be adjusted or repaired so that they have emissions equal to the other 79.3% of the buses, average smoke emissions would be reduced from 11.2% to 7.5%.

- Assuming a 60/40 mix of turbocharged and naturally aspirated buses, average smoke emissions would be reduced from 7.9% to 5.1%, a 35% reduction.

The cost effectiveness of the inspection and maintenance approach to reducing bus smoke levels cannot be estimated accurately until more detailed information is available regarding the adjustments and maintenance necessary to reduce smoke levels from those buses which are currently high emitters. However, the reduction in particulate emissions associated with modifications which make the high emitters perform like the lower end of the distribution is estimated to reduce the particulate emissions rate from buses by approximately one gram per mile.

Given the fact that the average bus accumulates approximately 50,000 miles per year, the annual reduction per bus would be in the neighborhood of 100 pounds per year. A cost-effectiveness ratio of $4.00 per pound would be achieved with an average expenditure of $400 per high emission bus. Assuming a fully-burdened labor rate of $30 per hour for the performance of smoke inspections, and an average time for the inspection and recording of the data of 10 minutes per bus every other month, it would cost $30 per bus/year for the inspections. Cost per high smoke bus per year would be $171 ($30/0.175). This would leave $229 per year for the cost of additional maintenance on high smoke buses. This is well within the cost that would be required for smoke related maintenance such as adjustment of the throttle delay mechanism on turbocharged buses. Although other types of maintenance that may be required to reduce smoke levels would be more expensive, this preliminary analysis indicates that the I/M concept for Diesel bus smoke is worth pursuing.

Improved Diesel Fuel Quality

For smoke emission control purposes only, requirements for improved Diesel fuel quality may be higher in cost than an inspection and maintenance program for transit buses. The cost-effectiveness of Diesel fuel specifications depends on whether credit is given to the effect such specifications would have on secondary particulates (i.e. particles formed through the atmospheric transformation of sulfur dioxide into sulfate).

Certain Diesel fuel specification requirements may be cost effective relative to other measures which have been adopted for the control of the total amount of fine particles in the atmosphere. In addition, the significant difference in costs associated with improving Diesel fuel quality for different refiners indicates that Diesel fuel specifications of more limited applicability (e.g., transit bus fuel only) could be significantly more cost-effective than the universal control of all Diesel fuel.

Retrofit Potential

Data from the literature and the field survey indicate that design improvements applicable to bus engines have recently been made in the areas of piston ring design, turbocharger matching, and transient fuel injection rate control. Incorporation of this technology on a retrofit basis may represent a practical and cost-effective means of further reducing smoke and particulate emissions from the turbocharged engines which are the highest smoke emitters.

The feasibility of incorporating improved technology during the rebuilding process appears to warrant further consideration. For example, piston ring design changes incorporated into some 1983 model Detroit Diesel Allison engines significantly reduced the level of lubricating oil transferred to the intake air charge on the 92 Series of line haul truck engines (13). This change contributed to reduced hydrocarbon and smoke levels. In 1983, GM also replaced the "Throttle Delay" mechanism on turbocharged 92 Series truck engines with a "Fuel Modulator" system. The new system has proven much more effective in reducing smoke and particulate emissions during acceleration (13).

Section 10

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Appendix A

Vehicle Specifications, Field Survey Results, and Maintenance History

DISTRICT	BUS NUMBER	PERCENT OPACITY	ENGINE MODEL	ENGINE MODEL YEAR	ASPIRATION METHOD	HORSE POWER	CAL OR FED	CURRENT MILEAGE	LAST REBUILD MILEAGE	LAST MAINT MILEAGE	LAST INJECT MILEAGE
SCRTD	1031	0	8V-71	73	N	245	F	572000	124000	12700	124000
SCRTD	1037	0	8V-71	73	N	245	F	475500	129700	5200	129700
SCRTD	1038	0	8V-71	73	N	245	F	469400	110600	15900	110600
SCRTD	1066	0	8V-71	73	N	245	F	520300	135800	1600	135800
SCRTD	1068	0	8V-71	73	N	245	F	540700	171500	16600	171500
SCRTD	1076	0	8V-71	73	N	245	F	514500	91600	7400	91600
SCRTD	1080	0	8V-71	73	N	245	F	553700	151800	1600	102800
SCRTD	3131	5	8V-71	74	N	254	C	403000	43600	2600	43600
SCRTD	3153	10	8V-71	74	N	254	C	407200	123200	5800	123200
SCRTD	3155	0	8V-71	74	N	254	C	373000	46300	6900	46300
SCRTD	3183	5	8V-71	74	N	254	C	438300	115200	2500	115200
SCRTD	3188	10	8V-71	74	N	254	C	445200	131200	1000	131200
SCRTD	3196	0	8V-71	74	N	254	C	437700	75100	6400	6400
SCRTD	3211	0	8V-71	74	N	254	C	500000	107100	5700	107100
SCRTD	3228	0	8V-71	74	N	254	C	414000	12800	7700	12800
SCRTD	3237	0	8V-71	74	N	254	C	435400	186500	15700	186500
SCRTD	3267	5	8V-71	74	N	254	C	354200	47200	7300	47200
SCRTD	3270	0	8V-71	74	N	254	C	428400	104900	10800	104900
SCRTD	3275	5	8V-71	74	N	254	C	479100	123100	10800	123100
SCRTD	3278	0	8V-71	74	N	254	C	440200	72200	4900	72200
SCRTD	3288	0	8V-71	74	N	254	C	482900	36000	3500	36000
SCRTD	3290	10	8V-71	74	N	254	C	474800	104900	9200	88200
SCRTD	3293	5	8V-71	74	N	254	C	493100	110000	5500	110000
SCRTD	3297	5	8V-71	74	N	254	C	477500	145500	2600	76000
SCRTD	3308	0	6V-92	84	T	294	C	39400	39400	1400	39400
SCRTD	3331	0	6V-92	84	T	294	C	22168	22168	3000	22168
SCRTD	3339	0	6V-92	84	T	294	C	35151	35151	3000	35151
SCRTD	3358	0	6V-92	84	T	294	C	24891	24891	6500	24891
SCRTD	3371	15	6V-92	84	T	294	C	25184	26184	7400	26184
SCRTD	3381	3	6V-92	84	T	294	C	43471	43471	6100	43471
SCRTD	3404	15	6V-92	84	T	294	C	42056	42056	3100	42056
SCRTD	3405	0	6V-92	84	T	294	C	36592	36592	3300	36592
SCRTD	3407	5	6V-92	84	T	294	C	39081	39081	1500	39081
SCRTD	3441	0	6V-92	84	T	294	C	35628	35628	400	35628
SCRTD	3472	0	6V-92	84	T	294	C	38687	38687	1000	38687
SCRTD	3498	0	6V-92	84	T	294	C	37030	37030	5600	37030
SCRTD	3528	5	6V-92	84	T	294	C	48037	48037	12200	48037
SCRTD	3575	5	6V-92	84	T	294	C	32747	32747	7000	32747
SCRTD	4227	0	6V-71	68	N	195	N	680500	10400	5200	10800
SCRTD	4332	0	8V-71	73	N	256	F	652600	164500	2700	27000
SCRTD	4422	0	6V-92	82	T	247	F	100000	100500	100	100500
SCRTD	6134	0	6V-71	68	N	195	N	633800	89100	11500	89100
SCRTD	7036	0	8V-71	71	N	271	F	633600	106600	0	106600
SCRTD	7206	0	8V-71	73	N	271	F	463700	203700	11500	75800
SCRTD	7226	0	8V-71	73	N	271	F	499400	92400	3400	92400
SCRTD	7229	5	8V-71	73	N	271	F	477200	90200	900	90200
SCRTD	7230	0	8V-71	73	N	271	F	467900	26800	7600	26800
SCRTD	7237	0	8V-71	73	N	271	F	450000	15800	8800	15800
SCRTD	7306	0	8V-71	75	N	225	C	584200	53200	18200	35700

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SCRTD	7363	0	8V-71	75	N	225	C	569700	185300	3500	185300
SCRTD	7370	5	8V-71	75	N	225	C	590200	137200	6100	137200
SCRTD	7384	2	8V-71	75	N	225	C	578700	121900	1600	121900
SCRTD	7414	0	8V-71	75	N	225	C	418000	88900	13300	88100
SCRTD	7433	0	8V-71	75	N	225	C	422000	83100	15500	68400
SCRTD	7468	5	8V-71	75	N	225	C	503300	36300	4800	28600
SCRTD	7469	0	8V-71	75	N	225	C	511000	106100	700	106100
SCRTD	7506	0	6V-92	80	T	254	C	199000	40000	2000	40000
SCRTD	7527	0	6V-92	80	T	254	C	174600	62000	14500	21100
SCRTD	7672	0	6V-92	80	T	254	C	144100	22000	13100	22000
SCRTD	7679	0	6V-92	80	T	254	C	127600	26300	1600	26300
SCRTD	7709	5	6V-92	80	T	254	C	170000	38700	15900	38700
SCRTD	8003	0	8V-71	78	N	254	C	183200	183200	2000	85900
SCRTD	8017	5	8V-71	78	N	254	C	227000	92900	5500	92900
SCRTD	8060	0	8V-71	78	N	254	C	205600	70900	5800	8800
SCRTD	8074	5	8V-71	78	N	254	C	241900	241900	1500	241900
SCRTD	8075	5	8V-71	78	N	254	C	237100	237100	12400	91500
SCRTD	8085	5	8V-71	78	N	254	C	240900	18200	200	18200
SCRTD	8099	10	8V-71	78	N	254	C	235500	235500	3400	235500
SCRTD	8190	15	8V-71	78	N	254	C	350400	113100	9500	113100
SCRTD	8214	45	6V-92	80	T	254	C	216900	216900	4400	73000
SCRTD	8248	5	6V-92	80	T	254	C	219900	62800	10000	62800
SCRTD	8256	10	6V-92	80	T	254	C	228600	228400	6100	228400
SCRTD	8262	15	6V-92	80	T	254	C	220400	220400	9800	114400
SCRTD	8278	15	6V-92	80	T	254	C	210800	210800	14400	33000
SCRTD	8280	30	6V-92	80	T	254	C	219700	219700	6200	219700
SCRTD	8286	10	6V-92	80	T	254	C	210300	28400	13700	28400
SCRTD	8306	20	6V-92	80	T	254	C	205100	205100	2600	3300
SCRTD	8313	20	6V-92	80	T	254	C	188400	188400	16100	36200
SCRTD	8324	15	6V-92	80	T	254	C	210300	210300	12700	153800
SCRTD	8328	15	6V-92	80	T	254	C	184500	184500	10700	184500
SCRTD	8334	25	6V-92	80	T	254	C	197600	197600	12800	153300
SCRTD	8336	13	6V-92	80	T	254	C	193600	193600	7600	193600
SCRTD	8344	10	6V-92	80	T	254	C	189100	189100	8800	38400
SCRTD	8346	15	6V-92	80	T	254	C	184200	184200	7500	184200
SCRTD	8348	15	6V-92	80	T	254	C	196500	500	4800	500
SCRTD	8356	15	6V-92	80	T	254	C	190800	33000	5100	33000
SCRTD	8358	0	6V-92	80	T	254	C	194900	7600	7400	7600
SCRTD	8360	20	6V-92	80	T	254	C	189800	189800	6600	189800
SCRTD	8361	15	6V-92	80	T	254	C	206500	206500	9500	161500
SCRTD	8364	15	6V-92	80	T	254	C	189000	189000	6000	189000
SCRTD	8366	5	6V-92	80	T	254	C	189100	189100	6700	38400
SCRTD	8369	10	6V-92	80	T	254	C	184200	184200	7500	184200
SCRTD	8374	10	6V-92	80	T	254	C	190400	190400	7900	97200
SCRTD	8377	10	6V-92	80	T	254	C	197400	39300	12000	39300
SCRTD	8381	5	6V-92	80	T	254	C	210500	210500	7100	210500
SCRTD	8382	20	6V-92	80	T	254	C	199700	16300	10000	16300
SCRTD	8387	0	6V-92	80	T	254	C	195900	600	6500	600
SCRTD	8389	15	6V-92	80	T	254	C	172700	172700	7000	44800

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SCRTD	8390	20	6V-92	80	T	254	C	179600	179600	3000	4100
SCRTD	8391	5	6V-92	80	T	254	C	190700	190700	5000	75900
SCRTD	8392	5	6V-92	80	T	254	C	190700	25900	7500	25900
SCRTD	8393	10	6V-92	80	T	254	C	203800	203800	10500	161800
SCRTD	8395	0	6V-92	80	T	254	C	199900	10100	11700	10100
SCRTD	8442	5	6V-92	80	T	254	C	237600	237600	400	237600
SCRTD	8450	0	6V-92	80	T	254	C	238600	8200	9300	8200
SCRTD	8546	25	6V-92	80	T	254	C	191900	11800	7800	11800
SCRTD	8560	10	6V-92	80	T	254	C	227400	25900	5000	25900
SCRTD	8600	20	6V-92	80	T	254	C	221400	13800	0	13800
SCRTD	8704	20	6V-92	80	T	254	C	184700	184700	7200	184700
SCRTD	8706	5	6V-92	80	T	254	C	146100	12100	8700	12100
SCRTD	8712	20	6V-92	80	T	254	C	185800	185800	4800	112900
SCRTD	8754	20	6V-92	80	T	254	C	193300	24700	16100	16100
SCRTD	8760	5	6V-92	80	T	254	C	210200	45300	11300	40700
SCRTD	8775	0	6V-92	80	T	254	C	204300	10000	4800	10000
SCRTD	8855	10	6V-92	80	T	254	C	207200	207200	15200	207200
SCRTD	8871	10	6V-92	80	T	254	C	187100	187100	11700	18900
SCRTD	8873	7	6V-92	80	T	254	C	187700	187700	10900	22700
SCRTD	8876	0	6V-92	80	T	254	C	170800	170800	6700	22000
SCRTD	8886	5	6V-92	80	T	254	C	189900	189900	7500	33200
SCRTD	8887	15	6V-92	80	T	254	C	180100	180100	5700	45800
SCRTD	8895	7	6V-92	80	T	254	C	186800	186800	14700	54000
SCRTD	8908	10	6V-92	80	T	254	C	174700	700	8400	700
SCRTD	8910	27	6V-92	80	T	254	C	176600	176600	13900	2400
SCRTD	8926	5	6V-92	80	T	254	C	164300	164300	11000	28100
SCRTD	8930	5	6V-92	80	T	254	C	175300	175300	12900	43000
SCRTD	8938	15	6V-92	80	T	254	C	153900	153900	8600	23400
SCRTD	8945	20	6V-92	80	T	254	C	222000	222000	6700	222000
SCRTD	9055	10	6V-92	80	T	254	C	189800	189800	1500	189800
SCRTD	9125	10	6V-92	80	T	254	C	220700	220700	4000	220700
SCRTD	9134	5	6V-92	80	T	254	C	204800	204800	1800	48900
SMMBL	4201	3	6V-71	73	N	238	C	358029	358029	50344	358029
SMMBL	4202	0	6V-71	73	N	238	C	371416	45022	5426	45022
SMMBL	4704	20	8V-71	79	T	350	C	143461	40134	39397	40134
SMMBL	4709	20	8V-71	79	T	350	C	152298	152298	240	65142
SMMBL	4710	20	8V-71	79	T	350	C	159820	69748	1788	69748
SMMBL	4714	27	8V-71	79	T	350	C	165811	36926	1683	36926
SMMBL	4717	7	8V-71	80	T	350	C	167863	35246	3961	35246
SMMBL	4718	15	8V-71	80	T	350	C	171043	171043	1099	72885
SMMBL	4723	7	8V-71	80	T	350	C	161225	161225	3340	32098
SMMBL	4729	10	8V-71	80	T	350	C	174775	68212	4815	68212
SMMBL	4732	5	8V-71	80	T	350	C	177583	53968	1593	53960
SMMBL	4735	40	8V-71	80	T	350	C	118519	31133	2600	11796
SMMBL	4737	10	8V-71	80	T	350	C	196371	196371	2195	119389
SMMBL	4739	10	8V-71	80	T	350	C	153135	59713	1242	59713
SMMBL	4743	14	8V-71	80	T	350	C	187280	77790	2295	77790
SMMBL	4747	37	8V-71	80	T	350	C	194327	47647	290	47647
SMMBL	4748	15	6V-92	81	T	330	C	137623	137623	5412	137623

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SMMBL	4750	30	6V-92	81	T	330	C	167037	167037	4950	85893
SMMBL	4751	15	6V-92	81	T	330	C	183182	183182	2812	98958
SMMBL	4752	20	6V-92	81	T	330	C	177720	177720	3647	177720
SMMBL	4755	8	6V-92	81	T	330	C	182656	182656	2641	11894
SMMBL	4757	40	6V-92	81	T	330	C	173399	173399	5161	82402
SMMBL	4758	10	6V-92	81	T	330	C	176199	176199	2158	176199
SMMBL	4759	10	6V-92	81	T	330	C	183270	183270	3314	183270
SMMBL	4761	10	6V-92	81	T	330	C	198285	198285	312	198285
SMMBL	4905	0	8V-71	73	N	318	F	410593	4307	701	4307
SMMBL	4908	0	8V-71	73	N	318	F	400547	13501	2657	13501
SMMBL	4914	0	8V-71	73	N	318	F	416282	4106	154	4106
SMMBL	4920	0	8V-71	73	N	318	F	425753	16857	3669	16857
SMMBL	4922	0	8V-71	73	N	318	F	392156	8828	107	8828
SMMBL	4923	0	8V-71	73	N	318	F	360429	7360	4559	7360
SMMBL	4924	0	8V-71	73	N	318	F	369412	11264	1548	11264
SMMBL	5104	10	8V-71	82	N	318	F	110235	110235	182	110235
SMMBL	5105	0	8V-71	82	N	318	F	99898	99898	1398	99898
SMMBL	5106	0	8V-71	82	N	318	F	118528	118528	2335	118528
SMMBL	5111	15	8V-71	82	N	318	F	128529	128529	308	128529
SMMBL	5112	0	8V-71	82	N	318	F	118117	118117	2026	118117
SMMBL	5113	5	8V-71	82	N	318	F	120683	120683	4531	120683
SMMBL	5116	7	8V-71	82	N	318	F	110942	110942	442	110942
SMMBL	5117	5	8V-71	82	N	318	F	99047	99047	1130	99047
SMMBL	5118	0	8V-71	82	N	318	F	119617	119617	3889	119617
SMMBL	5119	5	8V-71	82	N	318	F	100685	100685	2709	100685
SMMBL	5121	5	8V-71	82	N	318	F	116209	116209	204	116209
SRT	4150	5	8V-71	75	N	239	C	437410	183192	1406	65685
SRT	4153	8	8V-71	75	N	239	C	445305	187324	334	143843
SRT	4154	10	8V-71	75	N	239	C	428343	170524	7114	28369
SRT	4159	0	8V-71	75	N	239	C	465486	195774	3850	7116
SRT	4163	0	8V-71	75	N	239	C	505388	160059	1572	9827
SRT	4167	5	8V-71	75	N	239	C	472953	127624	865	67063
SRT	4171	0	8V-71	75	N	239	C	482415	135186	582	135186
SRT	4509	0	6V-71	65	N	183	N	826070	85864	2833	21149
SRT	4510	0	6V-71	65	N	183	N	775815	103377	1226	4419
SRT	4519	0	6V-71	65	N	183	N	774358	61349	4155	61349
SRT	4520	0	6V-71	65	N	183	N	755426	46229	766	22479
SRT	4522	0	6V-71	65	N	183	N	766732	41975	3335	41975
SRT	4523	0	6V-71	65	N	183	N	773144	72261	2075	72261
SRT	4524	0	6V-71	65	N	183	N	760491	0	1941	0
SRT	4525	0	6V-71	65	N	183	N	754444	27995	9180	27995
SRT	4527	0	6V-71	65	N	183	N	761611	68042	5764	68042
SRT	4528	15	6V-71	65	N	183	N	723419	63303	4164	12787
SRT	4529	10	6V-71	65	N	183	N	735998	126743	171	67310
SRT	4532	0	6V-71	68	N	183	N	640933	124164	1529	95668
SRT	4534	15	6V-71	68	N	183	N	681211	51152	4006	59089
SRT	4535	0	6V-71	68	N	183	N	676362	61798	1951	61798
SRT	4540	0	6V-71	68	N	183	N	695674	77717	3036	29942
SRT	4541	0	6V-71	68	N	183	N	630191	122671	3365	101408

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SRT	4542	0	6V-71	68	N	183	N	641360	6913	5904	6913
SRT	4543	0	6V-71	68	N	183	N	654904	71968	1255	62742
SRT	4544	0	6V-71	68	N	183	N	723553	67546	1965	67546
SRT	4545	0	6V-71	65	N	183	N	625538	41469	1695	23469
SRT	4547	0	6V-71	65	N	183	N	713041	48359	575	40803
SRT	4556	2	6V-71	68	N	183	N	599031	67646	3082	12541
SRT	4557	8	6V-71	68	N	183	N	615962	135074	3516	69654
SRT	4558	0	6V-71	68	N	183	N	581426	142361	2346	57368
SRT	4559	0	6V-71	68	N	183	N	515638	80998	3156	11741
SRT	4560	3	6V-71	68	N	183	N	561946	6195	2757	6195
SRT	4561	7	6V-71	68	N	183	N	598170	8639	951	8639
SRT	4562	0	6V-71	68	N	183	N	550594	64386	254	64386
SRT	4563	0	6V-71	68	N	183	N	582304	67331	4032	67331
SRT	4564	0	6V-71	68	N	183	N	559167	56854	3203	56854
SRT	4565	0	6V-71	68	N	183	N	548234	68226	4160	27747
SRT	4567	0	6V-71	68	N	183	N	546469	46942	5560	46942
SRT	4578	10	6V-71	65	N	183	N	652813	68453	9158	68453
SRT	4701	15	6V-92	82	T	270	F	111101	111101	452	111101
SRT	4702	5	6V-92	82	T	270	F	103399	103399	2702	103399
SRT	4703	5	6V-92	82	T	270	F	119475	110475	4744	110475
SRT	4704	10	6V-92	82	T	270	F	114256	114256	1570	114256
SRT	4705	10	6V-92	82	T	270	F	121964	121964	5481	121964
SRT	4707	10	6V-92	82	T	270	F	123429	123429	10027	123429
SRT	4710	13	6V-92	82	T	270	F	107776	107776	1285	107776
SRT	4711	15	6V-92	82	T	270	F	89103	89103	6623	89103
SRT	4713	10	6V-92	82	T	270	F	120658	120658	2305	120658
SRT	4715	10	6V-92	82	T	270	F	122781	122781	1720	122781
SRT	4717	10	6V-92	82	T	270	F	115196	115196	2959	115196
SRT	4718	10	6V-92	82	T	270	F	101458	101458	4393	101458
SRT	4906	0	8V-71	73	N	239	C	528106	161434	2903	98393
SRT	4916	0	8V-71	73	N	239	C	566125	152807	2764	40739
SRT	4919	0	8V-71	73	N	239	C	500903	138510	4159	22086
SRT	4920	0	8V-71	73	N	239	C	497562	193092	2199	53534
SRT	4921	0	8V-71	73	N	239	C	487104	191654	5195	101271
SRT	4927	7	8V-71	75	N	239	C	437259	86611	285	76957
SRT	4928	5	8V-71	75	N	239	C	462369	111898	3200	107108
SRT	4936	5	8V-71	75	N	239	C	453738	186729	4966	69667
SRT	4937	0	8V-71	75	N	239	C	429810	92966	2832	51994
SRT	4940	10	8V-71	75	N	239	C	439758	55400	1829	47149
SRT	4941	5	8V-71	75	N	239	C	365805	100830	4941	65111
SRT	4942	10	8V-71	75	N	239	C	441256	209748	496	6957
SRT	4944	0	8V-71	75	N	239	C	211130	139663	4681	92446
SRT	4946	10	8V-71	75	N	239	C	438984	129426	5925	21884
SRT	4948	7	8V-71	75	N	239	C	427477	90503	2552	70790
SRT	4949	0	8V-71	75	N	239	C	431402	49833	3728	49833
SRT	4952	5	8V-71	75	N	239	C	433902	80308	4183	65462
SRT	4954	0	8V-71	75	N	239	C	438244	113024	4668	84960
SRT	4956	15	8V-71	75	N	239	C	413914	57375	252	18141
SRT	4964	5	8V-71	75	N	239	C	427595	71796	992	45499

Appendix A

Vehicle Specifications,
Field Survey Results,
and Maintenance History

DISTRICT	BUS NUMBER	PERCENT OPACITY	ENGINE MODEL	ENGINE MODEL YEAR	ASPIRATION METHOD	HORSE POWER	CAL OR FED	CURRENT MILEAGE	LAST REBUILD MILEAGE	LAST MAINT MILEAGE	LAST INJECT MILEAGE
SRT	4965	15	8V-71	75	N	239	C	452334	96620	1952	85511
SRT	4967	5	8V-71	75	N	239	C	431968	78378	2277	12699
SRT	4973	5	8V-71	75	N	239	C	442307	82930	518	43934
SRT	4977	15	8V-71	75	N	239	C	453393	120125	12	38145
SRT	4981	10	8V-71	75	N	239	C	447329	85540	3406	60517
SRT	4985	5	8V-71	75	N	239	C	404563	127515	3231	116317
SRT	4986	10	8V-71	75	N	239	C	410108	71006	3971	71006
SRT	4989	5	8V-71	75	N	239	C	405374	91591	4212	47312
SRT	4991	0	8V-71	75	N	239	C	464832	117922	55	53736
SRT	4992	15	8V-71	75	N	239	C	419990	73588	862	73588
SRT	4994	0	8V-71	75	N	239	C	458489	135013	2061	25946
SRT	4997	5	8V-71	75	N	239	C	443215	150833	4549	65479
SRT	4999	5	8V-71	75	N	239	C	447168	85094	5915	63489
SRT	5150	0	6V-71	60	N	183	N	27124	27124	374	374
SRT	5152	0	6V-71	60	N	183	N	33091	33091	2266	33091
SRT	5153	3	6V-71	60	N	183	N	37597	37597	2137	37597
SRT	5154	0	6V-71	60	N	183	N	37866	37866	290	37866
SRT	5155	0	6V-71	60	N	183	N	33722	33722	321	33722
SRT	5156	0	6V-71	60	N	183	N	36819	36819	2283	36819
SRT	5157	5	6V-71	60	N	183	N	38598	38598	0	275
SRT	5158	5	6V-71	60	N	183	N	33120	33120	1784	33120
SRT	5159	0	6V-71	60	N	183	N	35520	35520	3740	35520
SRT	5161	10	6V-71	60	N	183	N	33576	33576	571	33576

Appendix B

Tabular Opacity Distributions
(Observed Peak Opacity)
Composite (All Districts)

			MBL			RTD			RT		MBL	
	All	Turbos	8V-71T (79C)350	8V-71T (80C)350	6V-92T (81C)330	6V-92T (80C)254	6V-92T (82F)254	6V-92T (84C)294	6V-92T 82F)270	Nat. Asp.	8V-71N (73F)318	8V-71N (82F)318
0≤ % OPACITY <5	112	20	0	0	0	10	1	9	0	92	7	4
5≤ % OPACITY <10	62	24	0	3	1	15	0	3	2	38	0	5
10≤ % OPACITY <15	43	29	0	4	3	14	0	0	8	14	0	1
15≤ % OPACITY <20	27	19	0	1	2	12	0	2	2	8	0	1
20≤ % OPACITY <25	14	14	3	0	1	10	0	0	0	0	0	0
25≤ % OPACITY <30	4	4	1	0	0	3	0	0	0	0	0	0
30≤ % OPACITY <35	3	2	0	0	1	1	0	0	0	0	0	0
35≤ % OPACITY <40	1	1	0	1	0	0	0	0	0	0	0	0
40≤ % OPACITY <45	2	2	0	1	1	0	0	0	0	0	0	0
45≤ % OPACITY <50	1	1	0	0	0	1	0	0	0	0	0	0
50≤ % OPACITY	0	0	0	0	0	0	0	0	0	0	0	0
MEAN % OPACITY	6.8	11.4	21.8	15.6	17.6	11.4	0.0	3.4	10.2	3.1	0.0	4.8
DATA POINTS	269	116	14	10	9	66	1	14	12	52	7	11

Appendix B

Tabular Opacity Distributions
(Observed Peak Opacity)
Composite (All Districts)

	MBL	RTD								RT		
	6V-71N (73C)238	8V-71N (71F)271	8V-71N (73F)245	8V-71N (73F)256	8V-71N (73F)271	8V-71N (74C)254	8V-71N (75C)225	8V-71N (78C)254	6V-71N (60'sN)195	8V-71N (73C)239	8V-71N (75C)239	6V-71N (60'sN)183
0≤ % OPACITY <5	2	1	7	7	4	8	6	2	2	5	9	34
5≤ % OPACITY <10	0	0	0	0	1	6	2	4	0	0	16	4
10≤ % OPACITY <15	0	0	0	0	0	3	0	1	0	0	6	3
15≤ % OPACITY <20	0	0	0	0	0	0	0	1	0	0	4	2
20≤ % OPACITY <25	0	0	0	0	0	0	0	0	0	0	0	0
25≤ % OPACITY <30	0	0	0	0	0	0	0	0	0	0	0	0
30≤ % OPACITY <35	0	0	0	0	0	0	0	0	0	0	0	0
35≤ % OPACITY <40	0	0	0	0	0	0	0	0	0	0	0	0
40≤ % OPACITY <45	0	0	0	0	0	0	0	0	0	0	0	0
45≤ % OPACITY <50	0	0	0	0	0	0	0	0	0	0	0	0
50≤ % OPACITY	0	0	0	0	0	0	0	0	0	0	0	0
MEAN % OPACITY	0.0	0.0	0.0	0.0	1.0	3.5	1.5	5.6	0.0	0.0	5.9	2.1
DATA POINTS	2	1	7	1	5	17	8	8	2	5	35	43

Appendix C

Regression Analyses

Composite Mileage Regressions

Sample	District	N	Intercept	Slope x 10^{-5}	R_2	RSS	MS	MEAN MILEAGE (K)
% OPAC vs. REBUILD								
All		268	3.29	3.30	0.0770	15,850	59.6	104
Turbos		116	7.39	3.48	0.0829	8,952	78.5	116
8V-71T(79C)350	SMMBL	4	24.3	-3.23	0.220	32.0	16.0	74.8
8V-71T(80C)350	SMMBL	10	22.1	-7.18	0.124	1,240	155	90.2
6V-92T(80C)254	SCRTD	66	6.71	3.56	0.121	4,302	67.2	133
6V-92T(81C)330	SMMBL	9	47.2	-16.8	0.0671	870	124	175
6V-925(82F)254	SCRTD	1		-- Insufficient Data --				
6V-92T(82F)270	SRT	12	17.8	-6.76	0.0502	100.9	10.1	112
6V-92T(84C)294	SCRTD	14	1.73	4.66	0.00405	368.4	30.7	35.8
NAT. ASP.		152	2.17	1.02	0.0184	2,827	18.9	95.0
8V-71N(71F)271	SCRTD	1		-- Insufficient Data --				
8V-71N(73F)245	SCRTD	7		-- Opacities = 0 --				
8V-71N(73F)256	SCRTD	1		-- Insufficient Data --				
8V-71N(73F)271	SCRTD	5	0.915	0.0989	0.0011	19.98	6.66	85.8
8V-71N(73F)318	SMMBL	7		-- Opacities = 0 --				
8V-71N(73C)239	SRT	5		-- Opacities = 0 --				
8V-71N(74C)254	SCRTD	17	0.938	2.78	0.108	213	14.2	93.2
8V-71N(75C)225	SCRTD	8	2.19	-0.726	0.0233	34.9	5.8	102
8V-71N(75C)239	SRT	35	8.48	-2.18	0.0397	736	22.3	116
8V-71N(78C)254	SCRTD	8	4.80	0.555	0.00945	170.3	28.4	149
8V-71N(82F)318	SMMBL	11	-9.12	12.3	0.0617	216	24.0	113
6V-71N(60'sN)183	SRT	43	1.69	0.753	0.0038	731	17.8	58.9
6V-71N(60'sN)195	SCRTD	2		-- Insufficient Data --				
6V-71N(73C)238	SMMBL	2	1.59	0.777	0.0043	739	17.2	58.5

Sample	District	N	Intercept	Slope x 10^{-5}	R_2	RSS	MS	MEAN MILEAGE (K)
% OPAC vs. INJECTOR								
All		268	5.05	2.32	0.0290	16,670	62.7	72.5
Turbos		116	9.62	2.32	0.0278	9,489	83.2	78.3
8V-71T(79C)350	SMMBL	4	29.2	-14.0	0.404	24.5	12.2	53.0
8V-71T(80C)350	SMMBL	10	25.6	-17.2	0.166	1,180	148	57.9
6V-92T(80C)254	SCRTD	66	9.435	2.52	0.0515	4,642	72.5	78.8
6V-92T(81C)330	SMMBL	9	24.3	-5.24	0.0913	848	121	128
6V-925(82F)254	SCRTD	1		-- Insufficient Data --				
6V-92T(82F)270	SRT	12	17.8	-6.76	0.0502	100.9	10.1	112
6V-92T(84C)294	SCRTD	14	1.73	4.66	0.00405	368.4	30.7	35.8
NAT. ASP.		152	2.46	0.991	0.0141	2,839	18.9	68.0
8V-71N(71F)271	SCRTD	1		-- Insufficient Data --				
8V-71N(73F)245	SCRTD	7		-- Opacities = 0 --				
8V-71N(73F)256	SCRTD	1		-- Insufficient Data --				
8V-71N(73F)271	SCRTD	5	-0.714	2.85	0.214	15.7	5.24	60.2
8V-71N(73F)318	SMMBL	7		-- Opacities = 0 --				
8V-71N(73C)239	SRT	5		-- Opacities = 0 --				
8V-71N(74C)254	SCRTD	17	1.33	2.62	0.105	213	14.2	84.1
8V-71N(75C)225	SCRTD	8	1.92	-0.485	0.0128	35.3	5.88	96.4
8V-71N(75C)239	SRT	35	6.51	-0.932	0.00437	763	23.1	59.7
8V-71N(78C)254	SCRTD	8	2.95	2.41	0.180	141	23.5	111
8V-71N(82F)318	SMMBL	11	-9.12	12.3	0.0617	216	24.0	113
6V-71N(60'sN)183	SRT	43	2.10	0.0815	0.00003	734	17.9	40.2
6V-71N(60'sN)195	SCRTD	2		-- Insufficient Data --				
6V-71N(73C)238	SMMBL	2		-- Insufficient Data --				