

**ADDENDUM**



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## 1. INTRODUCTION

The recognition of in-use diesel vehicles as major sources of oxides of nitrogen and inhalable particulate emissions as well as increasing public complaint about diesel smoke and odor has required the California Air Resources Board (ARB) to focus on the methods available for controlling in-use emissions for diesels. Under current regulations in California, diesel vehicles are exempt from any requirement for inspection. The State police are empowered to ticket vehicles that they believe to be excessively smoky but this law has not been uniformly enforced. The ARB is therefore interested in the development of diagnostic procedures for light-duty diesel engines that would allow inspectors or mechanics to identify (and potentially correct) malfunctions causing excessive emissions from diesels.

Under contract to the ARB, EEA had developed diagnostic procedures for light-duty gasoline powered vehicles equipped with three-way catalyst systems. The development of diagnostics for diesels has many common elements with that previous effort, and the development of diagnostics for diesels was included as an addendum to the earlier effort for gasoline powered vehicles. The ARB required that this effort focus on control of in-use smoke emissions, and suggest methods that could simultaneously control in-use hydrocarbon (HC), nitrogen oxides (NO<sub>x</sub>) and particulate emissions to the extent possible. Recognizing that much of diesel smoke emissions are from heavy-duty diesels, the ARB extended the scope of work to include both light-duty diesel vehicles (LDDV) and heavy-duty diesel vehicles (HDDV). At the same time, it was recognized that the available data did not permit as extensive an effort for heavy-duty vehicles, and this analysis for HDDV's does not provide as detailed a test specification as for LDDV's.

Excessive smoke emissions can occur during both steady-state and transient modes, and a preliminary investigation of the modes most objectionable to the public was performed prior to development of the diagnostic procedures.

Diesels can be smoky under many conditions, such as:

- Cold start smoke
- Smoke during transient modes
- Smoke at highway speeds
- White smoke

It was considered that cold start smoke, although common, was probably not a major factor in public complaint because it occurs for a limited duration and usually in residential neighborhoods or truck stops where human exposure is limited. White smoke is a unique phenomenon whose occurrence (under peculiar conditions) is thought to be rare. Smoke at highway speeds, though commonly observed, may not be significant as a source of public complaint because of air mixing which aids rapid plume dispersion, and the lack of pedestrians who are exposed to the plume minimizes the impact on public health. Smoke at low-speed transient and continuous modes is common in city driving, e.g., accelerating from a stop light or climbing a grade. It is also the most significant mode when a large number of pedestrians or slow speed vehicles are directly in the path of the smoke plume. This effort therefore focuses on the low speed, transient operating mode and the low speed continuous mode as the source of public complaint on smoke emissions. Visibility, odor and public health are affected by smoke under these operating modes and are therefore also of concern. Our analysis of the malperformances that lead to high smoke concluded that all vehicles with excessive continuous smoke at low speed would also have excessive smoke during transients, i.e., vehicles with continuous smoke problems were a subset of the vehicles with transient smoke problems. Accordingly, testing to identify

vehicles with transient smoke problems would automatically identify vehicles with both types of problems.

Diesel engines have long enjoyed a reputation for low in-use gaseous emissions and were available primarily in heavy-duty vehicles prior to 1978. Heavy-duty vehicles are subject to a smoke emission standard that limits both average smoke during specific engine operating modes as well as peak smoke at any operating mode. The wide-spread introduction of diesels in the light-duty fleet is a relatively recent phenomenon and concerns about particulate and smoke emissions have become widespread only since about 1980. As a result, the body of data on in-use emissions of smoke and particulate and on the types of malperformances in LDDV's that cause excessive smoke/particulate emissions is small. Data on the emissions from in-use HDDV's is even less, primarily because of the difficulty in obtaining and testing HDDV's.

Accordingly, a significant portion of this effort was devoted to a detailed engineering analysis of the components of the diesel engine whose malperformance could result in high smoke emissions. In diesel engines, combustion is primarily controlled by the fuel injection system and the different types of systems available in the market were studied. Based on discussions with the major manufacturers of diesel engines, EEA has developed a comprehensive (but not exhaustive) list of component malfunctions on diesels that are widely believed to be common causes of excessive smoke. In addition, information on future technologies such as particulate traps and EGR is also presented. The findings of our engineering analysis are detailed in Section 2.

Section 3 documents the available data from tests on in-use diesels. Although a few hundred diesel vehicles have been tested for gaseous emissions, the data base on smoke and/or particulate emissions is small for LDDV's, and virtually non-existent for HDDV's. In addition, a few states now require that diesel vehicles also be subject to an inspection.

Section 3 documents the tests used in states with active I/M programs for diesels (either LDDV or HDDV), and the actual failure rate of the diesel fleet that is occurring in each of the programs. Our findings show that current programs use relatively ineffective test procedures to detect smoky diesels and are experiencing hardly any failures on the test.

EEA has combined this knowledge gained from in-use testing and the engineering analysis to evaluate a series of program options to control smoke from diesel vehicles, and this evaluation is presented in Section 4. The section includes a detailed study of smoke measurement techniques, (both subjective and objective) an analysis of different test cycles to evaluate the benefits and deficiencies of each cycle and an analysis of potential component inspection programs that can be utilized in either a centralized inspection or a decentralized inspection and maintenance program. The data in this section presents the range of possible options available to the ARB to control smoke from in-use vehicles. It was found that control of smoke emissions would also be accompanied by reductions in hydrocarbon and particulate emissions. A separate inspection procedure for control of NO<sub>x</sub> emissions is also described in this section.

Section 5 presents EEA's recommendations for a centralized LDDV test procedure and our evaluation of the types of repairs that can be performed at the ARB specified cost limits of \$50 and \$100. In order to control NO<sub>x</sub> emissions, we have included a diagnostic procedure to check if the EGR valve is functioning. Because of the paucity of data, we have made only preliminary recommendations for testing heavy-duty diesels. Section 5 also includes data from five diesel cars that EEA tested on a number of cycles (including our recommended method) as a validation of principle.

Appendix A presents the Federal smoke certification procedure. Appendix B includes the specification of two models of smokemeters of the type recommended for inclusion on the inspection test.

## 2. ENGINEERING ANALYSIS OF THE CAUSES OF HIGH SMOKE

### 2.1 OVERVIEW

It is widely known that the compression ignition (diesel) engine produces more visible smoke than the spark ignition engine. However, a well designed and well adjusted diesel engine usually produces little visible smoke under most normal operating conditions. On the other hand, engine component malfunctions or maladjustments can easily lead to large increases in visible smoke, especially under city driving conditions where low speed and transient modes of operation are dominant. In this section of the report, the types of common malperformances are identified and their influence on smoke emissions evaluated. The purpose of this engineering analysis is to identify the component malperformances and the driving modes under which high smoke is likely to occur, and design an inspection program to test for smoke under precisely those conditions.

The fundamental causes of excess smoke are insufficient oxygen during combustion or a combustion temperature that is too low. After the fuel is introduced into a diesel combustion chamber, it undergoes complex precombustion reaction that can be likened to thermal or catalytic cracking. This is because hydrogen in the fuel molecule oxidizes much more readily than the carbon, and is stripped off the molecule first. In order for the carbon to oxidize, three conditions must exist. First, the carbon must be surrounded by sufficient oxygen for combustion--a difficult situation because of the hydrogen which preferentially combines with available oxygen. Therefore, adequate turbulence or mixing must be present to bring in a fresh supply of air. Second the temperature must be very high, and is ordinarily a result of the hydrogen combustion. Contact with a cooler surface (e.g., the walls of the combustion chamber) or expansion of the mixture can quench this reaction. Third, even with

sufficient oxygen and high temperatures, oxidation of the carbon takes place relatively slowly. Any abnormal increase in unburnt carbon gives rise to increased smoke (and particulate) levels and will be the direct result of the lack of one or more of the three prerequisites--time, temperature, and oxygen.

Potential causes of high smoke can be categorized. The fuel system is most important since it controls both the quantity of fuel injected and the timing of the injection which determines, to a large degree, the fuel-air mixing process.

The mechanical condition of the engine block and its intake and exhaust system can also have an effect on smoke emissions. This includes piston and valve conditions that reduce compression pressure or change the shape of the combustion chamber either as a result of excess carbon build-up or due to improperly designed replacement parts. Restrictions in the intake or exhaust tract can reduce air flow through the engine, as can turbocharger defects.

The effect of these malperformances is considered separately for light-duty and heavy-duty vehicles. The discussion, especially for heavy-duty vehicles, is based largely on information obtained from major diesel engine manufacturers. Because of the importance of the fuel system in controlling smoke emissions, a preliminary discussion on fuel injection is provided below.

## 2.2 FUEL INJECTION SYSTEMS

The fuel injection system meters the fuel to the engine, pumps it to a very high pressure and injects the fuel into the combustion chamber at the proper time and for the proper duration. In all diesel engines, the fuel injection system is intimately linked to the throttle and the governor.

In general, governors are of two types. The one commonly used in most light-duty diesels and several heavy-duty diesels is called the high-low governor, where idle speed and maximum RPM is controlled by the governor, which adjusts the high and low fuel stops. At all other intermediate conditions, fuel is controlled by the throttle setting. The second type of governor is called the all-speed governor. Here, the governor controls fuel quantity at all speeds and the throttle sets the governor control speed. During transient conditions, there is a major difference in the action of the two systems. During an acceleration at part-throttle, the all-speed governor raises the fuel quantity injected to the maximum fuel available at that instantaneous RPM, maintains it at that condition until the desired engine speed is reached and then reduces the fuel to stabilize the engine at desired speed. In contrast, the high-low governor controls fuel only at wide-open throttle conditions by setting the maximum fuel stop. Thus, a part throttle acceleration in a vehicle with an all-speed governor can be as smoky as a wide-open throttle acceleration in that vehicle.

Fuel metering is typically controlled by two different types of systems. One is called the pressure-time system where the control lever for fuel adjusts an orifice that determines fuel flow. This controls the feed pressure to the high pressure pump. In the second type, the fuel is metered by altering the effective stroke of the high pressure fuel injection pump. In the case of the pressure-time system, the natural maximum fuel flow curve of the pump declines as a function of RPM. Since the engine air flow volumetric efficiency decreases with RPM below peak torque RPM, the natural curve must be modulated by the governor. Maladjustments of such systems can lead to low speed smoke problems. In contrast, the second type of fuel control does not have such a strong RPM dependence and hence maladjustments can cause smoke increases at all RPM.

### 2.3 LIGHT-DUTY VEHICLES

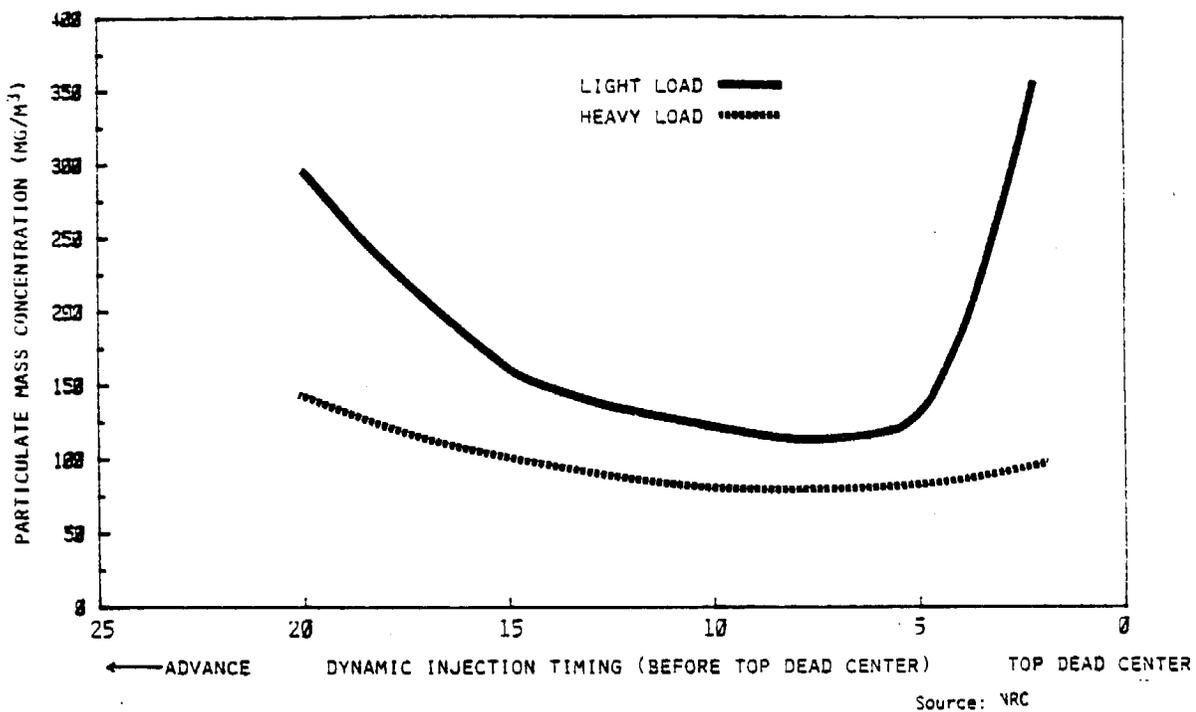
All light-duty vehicles are of the prechamber type where fuel is injected into a spherical prechamber that represents about 50 percent of the total combustion chamber volume. Fuel and air are premixed by very high air swirl rates before the partially burned mixture is blown out into the main chamber. In such engines, the combustion process is not as dependent on injection characteristics as the direct injection diesel. Potential malfunctions of the injection system are considered below.

Injection timing refers to the relation of the start of injection with respect to the piston top dead center. The adjustment is critical as a 5 degree error can lead to increased smoke and rough running. Figure 2-1 shows the typical response of a light-duty prechamber engine to injection timing changes. Smoke and particulate emissions increase with timing advance, and typically a 5 to 15 percent increase in smoke opacity at all speed/load conditions is associated with a 5 degree timing advance. Injection timing is controlled by the relative positioning of the injection pump drive to the crankshaft. The drive mechanism varies considerably by car model, ranging from belt drive to gear drive. Timing is a field adjustment in all vehicles and must be periodically checked; therefore, it has the potential to be maladjusted or malmaintained.

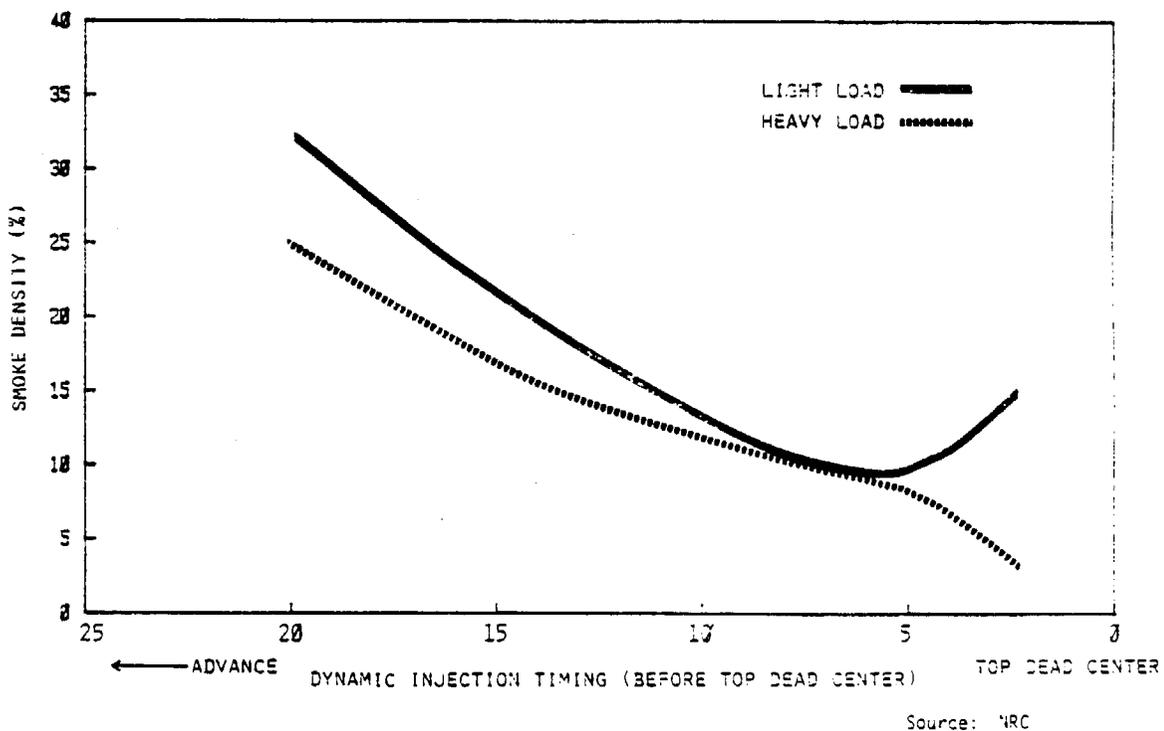
The fuel injectors are also a source of malperformances, as over time, they can foul-up or leak. Fouling is associated with the use of low quality diesel fuels and although it can reduce the quantity of fuel injected, it also can result in fuel spray deflection to the walls of the prechamber, causing high smoke. In addition, a leaky injector can lead to some fuel dribbling out well after end of injection; this leads to high smoke as well as rough running of the engine. This malperformance is also thought to be a likely cause of high smoke.

FIGURE 2-1

EFFECT OF INJECTION TIMING ON EMISSIONS  
PARTICULATE



EFFECT OF INJECTION TIMING ON EMISSIONS  
SMOKE



Types of maladjustments of the injection pump vary by the make and model of the vehicle, but in general, these maladjustments effectively increase the total fuel delivered at full throttle conditions. Most injection pumps are factory set and the adjustments are sealed; a pump calibration stand is usually required for proper adjustment. Since only a few types of fuel pumps are used on the more common diesel engines, each one is discussed specifically. The most common engines in use are the Oldsmobile 5.7 liter V-8, the Volkswagen 1.6 liter or 1.7 liter 4-cylinder and the Mercedes 3 liter 5-cylinder engine, usually turbocharged. Each of these engines uses a different type of pump and each will be treated separately.

The Oldsmobile engines (the 5.7 liter V-8's as well as the newer 4.3 liter V-6) all use a distributor pump made by Stanadyne called the Roosa-Master Model DB-2. The Chevrolet 6.2 liter (now made by Detroit Diesel Division) and the International Harvester 6.9 liter engine used by Ford both also use the same pump. This design of pump has been the most commonly manufactured pump in the world and is made under license by Lucas (U. K.) and RotoDiesel (France). It incorporates a pressure-time hydraulic metering system in that the control lever adjusts an orifice that determines fuel flow. In order to improve the accuracy a mechanical centrifugal governor is also incorporated. The control lever idle stop adjusts low idle speed and the full load stop adjusts max. fuel delivery, and both stops are normally factory sealed. High idle speed is adjusted internally. Since both the idle and full-load stops are easily accessible, tampering is very easy and the maladjustment is usually of the full-load fuel stop. The real difficulty is that the pump could be adjusted for legitimate reasons and the seal or safety wire broken in the process and there would be no way to tell the difference.

Another common distributor pump in use on passenger cars is the Bosch Model VE. This pump is used by Volkswagen, Peugeot and Renault among others. While similar externally this pump uses a different metering principle than the Stanadyne pump. A metering sleeve is slid over the

pump plunger by the control lever with the governor overriding the control at low and high idle speeds. In this case, the control lever stop controls the high idle speed. Maximum fuel delivery is controlled by a separate screw stopped with a locknut and sometimes safety wired. It is doubtful that service personnel reseal the screw after a legitimate adjustment making it impossible to verify subsequent tampering.

The third common design is the Bosch inline pump used on Mercedes 5-cylinder engines. A longitudinal rack turns pump barrels to vary fuel flow and an adjustable stop limits travel. Typically an easily removed cover encloses the adjusting screw for the full-load fuel stop. In the case of turbocharged engines a pressure sensitive device is fitted with a screw adjustment. In either case, adjustment is not difficult in the field. However, most car manufacturers believe that the unauthorized or improper adjustment of the full-load fuel stop in the Bosch pump is rare.

EEA conversations with diesel mechanics reveal that maladjustment of the full-load fuel stop may occur in certain specific models which are very underpowered. Manufacturers usually set the maximum fuel limit at the engine smoke limit, but maximum power (at high smoke) is attained with more fuel. Maladjustment of the stop is therefore an attractive means of increasing power at full throttle. Such maladjustments obviously increase smoke only under full throttle conditions.

Reductions in intake air flow effectively are similar to an increase in fueling. The most common cause is the dirty air filter, which can lead to large increases in smoke at high engine RPM. Experience with gasoline engines suggests that this is probably a common malfunction. Turbocharger damage can have similar effects, but this is thought to be extremely rare, and it is likely to be obvious to the vehicle owner.

Defects in the intake/exhaust valves or loss of compression can also lead to high smoke, as can excessive oil consumption. Such defects have

been known to occur in specific model year GM and VW vehicles. Problems with these vehicles have received widespread attention and it is likely that such engines have been repaired under settlements with the manufacturer. In other cases, such defects are usually associated with vehicles near the end of their useful life.

Two technologies that have recently appeared on diesel engines are EGR and the particulate trap and the observations below are based on comments from the manufacturers.

The EGR system employed in diesels is very similar to the one in gasoline vehicles. The EGR is utilized for NO<sub>x</sub> control and can cause high smoke if the EGR valve fails in the wide-open condition. However, driveability suffers greatly in this condition and most manufacturers believe that this type of failure is rare or likely to be fixed by the owner. It is more probable that the EGR fails in the closed position preventing recirculation of exhaust gas, and this condition can be caused by tampering. This failure, however, reduces smoke emissions although NO<sub>x</sub> emissions can rise by as much as 50 percent.

The particulate trap reduces smoke emissions substantially--to the point where any visible smoke emissions would suggest some form of trap malfunction. The trap must be periodically regenerated to clean out or oxidize the collected particulate and this is usually accomplished catalytically or by an external regeneration mechanism. The only trap that is commercially marketed today is on the California Mercedes 300 series, which utilizes a catalytic trap. The Mercedes workshop manual requires only a backpressure inspection to ensure that the catalytic regeneration does, indeed, take place. Detailed discussion with the manufacturers reveal that too much particulate buildup without regeneration will cause the engine to be inoperable, but there is also a danger of thermal damage to the trap when regeneration takes place. In a written response, Ford summarized the various forms of damage that can occur to the trap and

their tabular response is provided in Table 2-1. Ford's response is in agreement with the comments provided by other diesel manufacturers.

Table 2-2 summarizes all of the major malfunctions causing high smoke that can occur in LDDV's. The examination of the driving cycle under which each of these malperformances can cause excessive smoke revealed that, while some malperformances cause continuous smoke at all driving conditions, all of the malperformances would cause smoke during a transient acceleration mode that covered the range of engine RPM encountered in normal driving.

#### 2.4 HEAVY-DUTY VEHICLES

Unlike the light-duty diesel, almost all heavy-duty vehicles are direct-injection diesels, and a large fraction of the fleet is turbocharged. Another major difference is in the use of these diesels; while light-duty diesels are used infrequently at high load/speed conditions, trucks spend nearly all of their operating time near the maximum load/speed condition.

The three major diesel engine manufacturers contacted by EEA for this study--Cummins, Caterpillar and Detroit Diesel Allison (DDA)--utilize substantially different fuel injection systems. The DDA engines utilize the so-called "unit injector" where each cylinder has a completely separate metering and high pressure unit that is integrated into the cylinder head. Metering is accomplished by varying the effective stroke of the high pressure plunger. Since each individual injector is metered separately, all injectors in a individual engine must be indexed with respect to the common injector control tube controlling all injectors. The injector control tube is connected to governor/throttle by means of a fuel rod assembly. In general most DDA engines use a high/low governor although the all-speed governor is available as an option. Fuel injection at high pressure is accomplished by a rocker arm on the camshaft depressing the plunger for each injector. Injection timing is set by adjusting the injector follower height in relation to the injector body.

TABLE 2-1

## POTENTIAL TRAP MALFUNCTION

<u>Problem Area</u>	<u>Effect</u>	<u>Detection Test</u>
Filter failure due to thermal shock crack, melted ceramic, or mounting system failure	Increased particulates, reduced pressure rise rate, improved engine performance	Measure particulates and compare to reference levels
Thermal regeneration system	Failure to regenerate due to exhaust dilution of heating system - this will result in power loss	Inspect valve motion when triggered manually
Burner or electrical heating system fails	Failure to regenerate and loss in power. Possible fire and trap melting when regeneration is forced	Special diagnostic parts would have to be provided to check temperature rise for regeneration
Regeneration trigger sensor fails	Same as above	Same as above
Catalytic Regeneration System		
Catalyst deteriorates	Failure to regenerate and loss in power. Possible fire and trap melting when regeneration is forced.	Check for regeneration with back pressure measurements at high load condition where regeneration should occur
Fuel additive system fails	Same as above	Same as above
Engine malfunction causing high particulates due to sticking injector, low cetane fuel, high WCR	Frequent regeneration  Potential for fire and trap melting	Regeneration frequency test over a known cycle

Source: Ford Motor Co.

TABLE 2-2  
CAUSES OF SMOKE/ODOR IN  
LIGHT-DUTY DIESELS

- REDUCTIONS IN INTAKE/EXHAUST FLOW
  - DIRTY AIR FILTER (COMMON)
  - VALVE PROBLEMS (RARE)
  - TURBO CHARGER DAMAGE (RARE AND IMMEDIATELY OBVIOUS)
  - RESTRICTED EXHAUST OR TRAP BLOCKAGE
  
- FUEL DELIVERY
  - ADVANCED INJECTION TIMING (COMMON)
  - TAMPERED FULL-LOAD FUEL STOP (MAY BE COMMON IN SOME MODELS, E.G. GM)
  - LEAKING OR STICKING INJECTORS (CAN BE CAUSED BY FUEL OR ADDITIVES)
  - THROTTLE LINK/RACK OFFSET
  
- ENGINE PROBLEMS (MORE LIKELY IN OLD ENGINES)
  - LOSS OF COMPRESSION
  - CARBON ACCUMULATION IN COMBUSTION CHAMBER
  - OIL SEEPAGE PAST RINGS/VALVE GUIDES
  
- WHITE SMOKE - RETARDED TIMING
  - INJECTOR NOZZLES PARTIALLY CLOGGED
  
- EGR VALVE OPEN CONTINUOUSLY
  
- TRAP MALFUNCTION

Cummins engines also utilize a high pressure injector system driven by the camshaft through a rocker arm assembly, but fuel metering is done separately with the aid of a metering pump. The metering pump uses the pressure-time system where fuel pressure feeding the injectors (rail-pressure) is modulated through an orifice. Cummins engines use a hi/low governor typically, although an all-speed governor can be specified as an option, in most of their heavy-duty engine lines.

Caterpillar engines utilize a separate high-pressure in-line fuel injection pump much like the Mercedes light-duty diesel pump, although the governor used is typically an all-speed governor. The discussion above illustrates the difficulty in deriving a common list of malperformances for these different system types. Note that two other major manufacturers, International Harvester and Mack are not covered in this discussion; their injection systems also have some peculiarities.

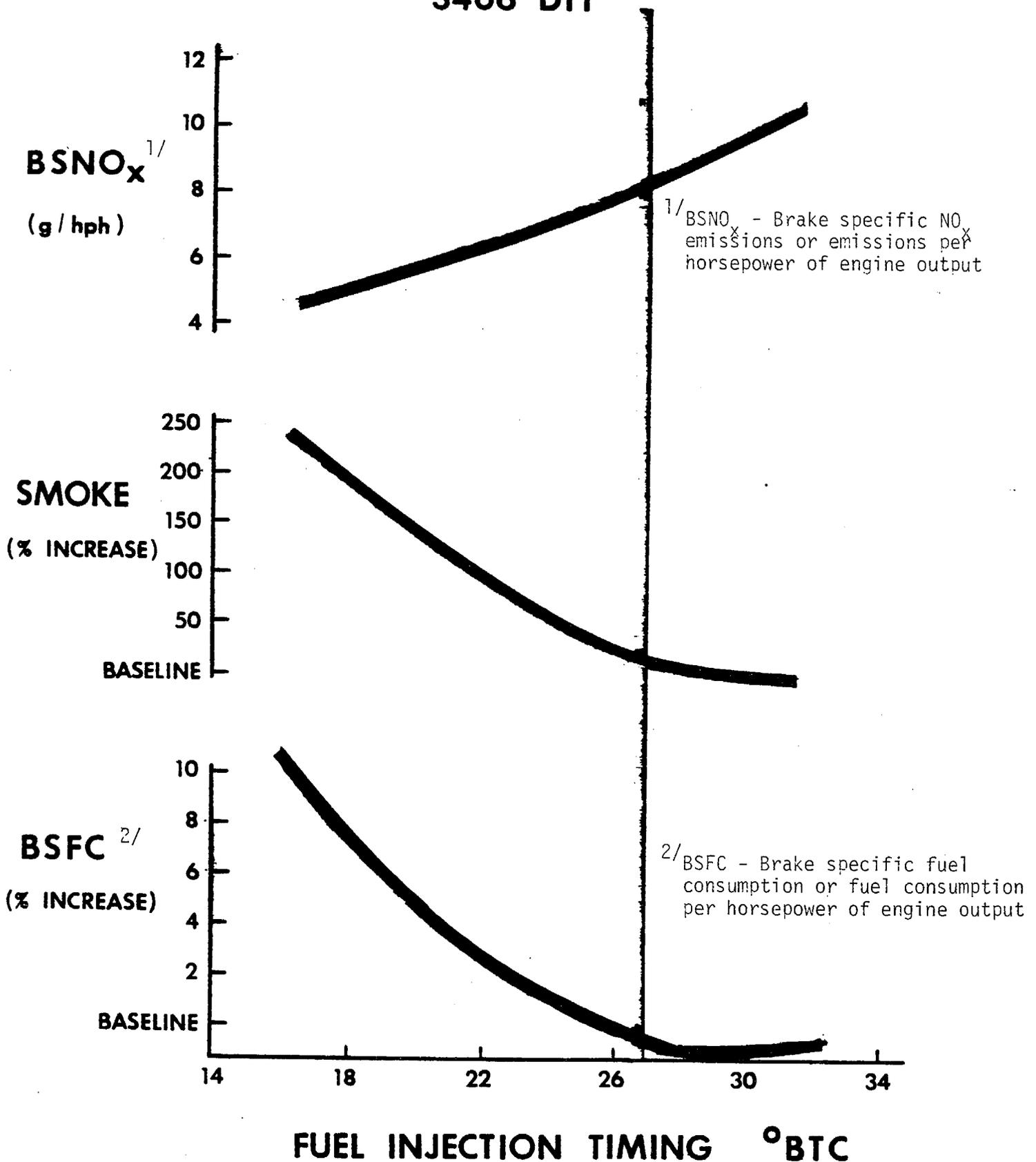
Injection timing is a critical determinant of smoke emission in HDDV's. In contrast to light-duty vehicles, timing retard causes increased smoke in direct injection diesels. Figure 2-2 shows the sensitivity of smoke emissions as a function of timing on a typical heavy-duty diesel (note that the X-axis is reversed in comparison to Figure 2-1 for light-duty diesels). Very large increases in smoke occur with timing retard, but the fuel consumption is increased, providing little incentive for such tampering. Moreover, injection timing is very difficult to change in DDA and Cummins engines and requires removal of the camshaft or major disassembly of the engine block. Most manufacturers were of the opinion that timing changes in HDDV's are not a major cause of smoke.

The malfunction or tampering of the smoke-puff limiter or air-fuel control may be common according to most manufacturers. This device limits the fuel during transient acceleration until the inlet pressure of air is high (i.e. the turbo boost is available) and tampering with this device is an easy way of obtaining more power during transients, albeit with

FIGURE 2-2

# EMISSIONS & FUEL CONS. vs TIMING

## 3406 DIT

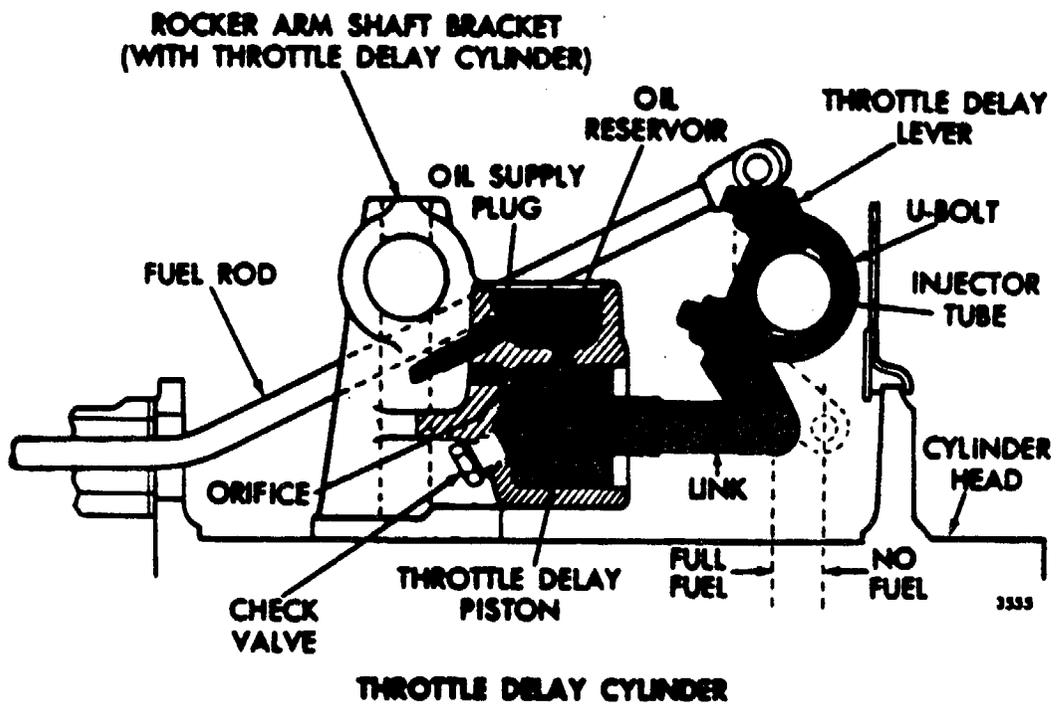


high smoke emissions. In DDA engines, the fuel rod activates the injector control tube through this device; the device is merely a dashpot that translates a transient acceleration to a slow increase in the control tube motion and effects a delayed throttle response (Figure 2-3). In Caterpillar engines, the device limits rack travel as a function of boost pressure, while in Cummins engines, the fuel rail pressure is bled off as a function of boost pressure. The DDA and Caterpillar devices can be completely disabled or removed, while the Cummins device can be adjusted so that the bleed is minimized.

The setting of the governed speed is another common maladjustment. Depending on the governor, these may be separate control settings for the maximum speed and the maximum fuel quantity or in some cases, only the setting for speed. With many governors, changing the governor maximum speed setting also changes the entire maximum fuel flow curve, leading to high smoke emissions. In most cases, this setting can be changed by an adjustment screw, which is sealed. However, many heavy-duty truckers are known to tamper with this setting to provide speed increases; in fact, special tools (called "stingers") are available to adjust this setting after drilling out the protective covers.

Injector malfunctions is also a probable cause of high smoke, although this is likely only on older engines and leads to rough running of the engine and poor performance. Typically, injectors accumulate varnish and dirt with time, giving rise to assymetric spray patterns. These spray patterns cause locally rich air-fuel ratios within the combustion chamber, and high smoke emissions is the result. The erosion of the injector spray holes is also common, leading to poorer atomization of the fuel and higher smoke. Leaky or broken injectors lead to very high smoke, but the performance is so poor tht it is unlikely that trucks can continue operation for any length of time. In DDA engines, misadjustment of the individual injectors can lead to some cylinders being more smoky than others.

FIGURE 2-3  
SMOKE PUFF LIMITER (DDA)



Air-flow restrictions can occur, leading to high smoke. Obvious reasons include dirty air filters and damaged turbochargers, but turbocharger damage is expected to be rare and obvious due to the sharp drop in available power. Valve leaks and low compression may occur in old engines, but because of the high load operation normally experienced by heavy-duty diesels, such malfunctions extract a heavy penalty on performance and are not likely to be commonplace.

Manufacturers could not provide any information on traps as their design and use on heavy-duty trucks is still very uncertain.

An engine "malfunction" mode unique to heavy-duty trucks is the engine that is rebuilt with mismatched parts. All heavy-duty engines are sold in a variety of horsepower ratings; while all ratings utilize a common engine block, each rating uses a special combination of injector size, turbocharger, piston type, injection pump settings, etc. These parts are closely matched to provide the air flow, fuel flow and swirl needed to minimize smoke especially at full load. Many independent engine rebuilders may not utilize the correct combination of parts--called the "critical parts list"--leading to high smoke when mismatched air/fuel flow conditions occur. Manufacturers suggest that this may be common for the high volume engines where a large number of independent suppliers provide parts. Similarly, excessive carbon buildup in the combustion chamber can alter combustion chamber air flow and swirl characteristics to increase smoke. Such buildup may be present in older engines near the end of their useful life before rebuild. Table 2-3 summarizes our findings on the heavy-duty malperformances that can lead to high smoke.

TABLE 2-3  
CAUSE OF SMOKE/ODOR IN  
HEAVY-DUTY DIESELS

- REDUCTIONS IN INTAKE AIR FLOW
  - AS FOR LIGHT-DUTY DIESELS
  
- FUEL DELIVERY
  - RETARDED INJECTOR TIMING (NOT LIKELY)
  - RAISED GOVERNED SPEED (ESPECIALLY FOR INDEPENDENT TRUCKERS)
  - MALADJUSTED TURBO-BOOST FUEL COMPENSATION OR THROTTLE DELAY (VERY COMMON)
  - TAMPERED FULL-LOAD FUEL STOP (LESS COMMON)
  - INJECTOR FOULING OR HOLE EROSION (COMMON)
  - OVERHEAD ADJUSTMENT (DDA ONLY)
  
- ENGINE PROBLEMS
  - "CRITICAL PARTS LIST" NOT FOLLOWED DURING REBUILD (MAY BE COMMON)\*
  - TURBO MISMATCH (RARE)
  - CARBON BUILDUP IN COMBUSTION CHAMBER
  
- EGR NOT LIKELY FOR HDD'S
  
- LITTLE INFORMATION ON TRAP TECHNOLOGY

\*NOT FOR FACTORY REBUILT ENGINES



### 3. REVIEW OF DATA FROM IN-USE DIESEL EMISSION TESTING AND DIESEL I/M PROGRAMS

#### 3.1 OVERVIEW

Diesel gaseous emissions have been known to be low in comparison to uncontrolled gasoline engine gaseous emissions, and little attention has historically been placed on evaluating their in-use performance. The introduction of low-priced light duty diesel vehicles (LDDV) and concerns about particulate emissions have led to a few recent studies on the FTP emissions of in-use diesels by the EPA, CARB and Colorado Department of Health. None of the studies, except one by Colorado, address the problem of smoke emissions from light-duty diesels. The data on in-use heavy-duty diesels (HDDV) is also small, although these diesels have been in widespread use for two decades. The only data that EEA found on in-use HDD's are the results of tests on 30 vehicles conducted by South-West Research Institute. The tests also address only gaseous and particulate emissions but provide no data on smoke.

Several states do have laws to control excessive smoke from diesels. In many, the law merely provides for traffic police to issue a citation to vehicles that they have subjectively determined as being "excessively smoky". Other states provide some training to police officers with the aid of a Ringelmann chart that introduces a degree of objectivity to the visual determination of excessive smoke. Only three I/M programs in the country include diesel vehicles and inspect them on a regular basis, but even here, the test methods appear to be flawed or of limited usefulness.

In this section of the report, a detailed review of the available data from tests on in-use diesels is provided. State I/M programs for diesels are documented and available results are summarized. Our conclusions from the available data are provided at the end of this section.

### 3.2 FTP TESTS OF IN-USE DIESELS

Tests results available from the EPA, CARB and Colorado were analyzed to identify common problems and malperformances in light-duty diesels and their impact on emissions.

EPA testing of light-duty diesels began with the FY1975 Emission Factor Program. However, both the FY75 and FY77 Programs consisted of relatively old Mercedes diesels, whose unique cost and durability characteristics make them not as relevant to this study as the study of more common diesels. The average emissions of the vehicles tested in each program are:

Program	N	HC*	CO*	NO <sub>x</sub> *	Odometer (miles)
FY75	20	0.80	2.2	1.60	76473
FY77	20	1.12	2.9	1.43	86318

As shown, average emissions for all vehicles are well below applicable standards inspite of the fact that these cars have very high mileage. However, applicable standards for pre-1978 LDV's are not very stringent and neither the malperformances nor the particulate/smoke emissions were measured in these studies.

In 1980, EPA published a study of 20 high mileage 1978 Oldsmobile diesels. Average emissions were 0.80HC/1.6CO/1.35NO<sub>x</sub>/0.85Particulate (g/mi) while the average odometer was 49,000 miles. In comparison, certification levels were 0.78HC/1.8CO/1.9NO<sub>x</sub> showing that there was little, if any, in-use deterioration. (No particulate standard was in force in 1978). Only two of 20 vehicles marginally exceeded the 1.5 g/mi HC standard, while one marginally exceeded the 2.0 g/mi NO<sub>x</sub> standard. No diagnostics on the high emitters was provided.

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\*Emissions in g/mi

In 1980, EPA published a study of 20 diesel LDT's consisting of 17 GM 1978/1979 LDT's, two 1977 IH Scout utility vehicles (with a Perkins diesel) and one 1978 Scout. Average emissions were 0.87HC/1.97CO/1.80NO<sub>x</sub> and the average odometer was 23,500 miles. Only one vehicle--a 1977 IH vehicle--exhibited high emissions of 3.33 g/mile HC. The other 1977 IH also exhibited relatively high HC emissions, at 1.47 g/mi, a level which meets applicable standards for 1977, but is substantially higher than the other 18 vehicles. Malperformances in these vehicles were not identified.

The CARB has conducted three vehicle surveillance programs on diesels. In the first series, 50 diesel vehicles from model years 1970-1979 were tested and average emission levels were 0.48HC/1.53CO/1.62NO<sub>x</sub> with an average odometer of 47,000 miles. Only two vehicles failed the applicable standards, and both failures were as a result of NO<sub>x</sub> emissions being marginally over 2.0 g/mi. These two, and four other vehicles that were not in manufacturer specification (based on engine inspection) were repaired and retested. The four other vehicles were: a 1975 Mercedes 300D, two 1972 Mercedes 220D's and a 1978 VW Rabbit. In two cases, "repairs" were very minor, exhaust valve lash was adjusted in two cases and injection timing was adjusted in two. On one of the vehicles whose timing was adjusted, the entire injection system was cleaned and the fuel line flushed due to "problem fuel". Comparison of before and after repair emissions showed an approximate 25 percent reduction for all three pollutants. However, all of the HC reduction was from the two vehicles whose timing was adjusted, and HC emissions declined by over 50 percent on these two vehicles after repair.

The CARB also measured particulate emissions for nine of the 50 vehicles tested. The vehicles included two GM vehicles, five Mercedes, one VW and one Peugeot. Both GM vehicles and two Mercedes vehicles exceeded the 0.6 g/mi limit (no standard for particulate emissions was in force

at that time). Average particulate emissions was 0.62 g/mi and ranged from 0.28 to 1.11 g/mi. None of the four high particulate emitters were repaired and none of them showed abnormally high HC emissions.

In the second surveillance series, CARB tested 44 diesel LDV's and LDT's from Model Year (MY) 1980 and 1981 with an average odometer of 16,400 miles. Although average emissions of 0.33HC/1.25CO/1.34NO<sub>x</sub> are low, 12 of 44 vehicles failed applicable standards. Particulate emissions from all vehicles showed only one vehicle exceeding 0.6 g/mi and five exceeding 0.4 g/mi, but no particulate standards were in effect. Of the 12 "failing" vehicles, nine were because of NO<sub>x</sub> emissions exceeding the 1.5 g/mi standard, and three because of high HC emissions. Five of the nine vehicles with high NO<sub>x</sub> emissions were diagnosed as having EGR problems and one a timing problem, while the remaining three exceeded the 1.5 g/mi marginally but the components were within specification. Of three vehicles exceeding the HC standard (all VW), two were diagnosed as having faulty injectors, while the third was a marginal failure with no observed defects. Repair of the EGR resulted in substantial (35 percent) reduction in NO<sub>x</sub> emissions with no effect on HC emissions, while changing the injectors reduced HC emissions by about 50 percent with small increases in NO<sub>x</sub> emissions. However, in all cases where NO<sub>x</sub> emissions were decreased, particulate emissions rose significantly. HC emissions and particulate emissions declined for the two vehicles with injector repairs. On average, a 20 percent reduction in both HC and NO<sub>x</sub> emissions were observed for all repaired vehicles.

EEA also received emission results for 30 in-use LDDV's that have been tested under the ongoing third surveillance program conducted by CARB. All of the vehicles are MY 1980-1982 and 22 of 30 vehicles have in excess of 50,000 miles (one has 100,139 miles) on the odometer. EEA's analysis of results shows:

- All nine GM 350 CID diesels tested failed emission standards-- five failed NO<sub>x</sub> standards, two failed HC standards and two failed both NO<sub>x</sub> and HC standards. The common malfunctions were of the EGR system and injection timing, but one vehicle had bad injectors as well.
- Of eight VW's tested, only one failed emissions standards. The failure was for HC emissions, and was caused by bad injectors. Minor timing maladjustment was found on two other vehicles.
- No defects were found on five Mercedes vehicles tested, although one exceeded NO<sub>x</sub> standards marginally.
- Of four Peugeot's tested, two failed emission standards. One vehicle had marginally high NO<sub>x</sub> emissions, while the second failed both HC and NO<sub>x</sub> standards. This second vehicle had defective EGR and bad injectors.
- No defects were found on four other vehicles--two Datsun's, one Volvo and one Isuzu--and all of these vehicles met emission standards.

Although it was not true in every case, vehicles with high HC emissions generally had high particulate emissions. Seven of 30 vehicles (five GM, one Peugeot, one Mercedes) exceeded the 0.6 g/mi particulate level; this standard applied only to 1982 vehicles, however. Typically, repair of EGR systems resulted in a NO<sub>x</sub> decline of 30-35 percent, while repair of timing and/or injector malfunction resulted in HC emission reduction of over 50 percent.

The Colorado Department of Health tested 20 LDDV's and 15 LDDT's that were all from model years 1978-1980. It must be noted that tests were performed at high-altitude, which tends to raise the emission of HC and particulate. All of the LDDV's except one 1980 GM vehicle passed applicable standards; the one failure was for high HC emissions. However, since Federal standards for 1978 and 1979 are relatively lax, we compared the emission results to the 0.54/7.0/1.5 California 1980+ standards. The results showed that:

- Of seven GM 350 CID vehicles, three failed the HC emission criterion and one failed both HC and NO<sub>x</sub> criteria. All four vehicles exhibited high particulate emissions, i.e., over 0.6 g/mi.
- Of five VW Rabbits tested, two failed the HC emission criterion, but only one had high particulate emissions.
- Of five Mercedes vehicles, only one vehicle displayed high emissions. NO<sub>x</sub> emission for this vehicle was at the applicable standard of 2.00 gm/mi, and another vehicle marginally exceeded the 1.5 g/mi criterion.
- Of three Peugeot vehicles, one vehicle failed the HC criterion, but had low particulate emissions.

The 15 LDDT's tested were all GM 350 powered trucks with one exception, an IH Scout. All vehicles tested were remarkably close to the average values of 1.33HC/3.15HC/1.45NO<sub>x</sub> 0.995 Particulate (g/mi) and the data shows a moderate degree of correlation between particulate and NO<sub>x</sub> emissions (i.e., those vehicles with NO<sub>x</sub> emissions higher than average had particulate emissions lower than average and vice-versa). No diagnostics were provided for either the LDDV's or the LDDT's.

More recently, Colorado performed tests on 20 MY 1981-82 LDDV's. In this program, five "failed" vehicles were repaired. The program is also unique in that smoke opacity was measured during the FTP cycle. The results are:

- Of five VW's tested, two failed to meet standards as a result of high HC emissions.
- Of nine GM vehicles tested, five vehicles failed to meet standards as a result of high HC emissions (one had the highest HC emissions recorded at 3.1 g/mi) and one vehicle failed for high NO<sub>x</sub> emissions. In addition, two vehicles marginally failed NO<sub>x</sub> standards.
- Two Mercedes-Benz 300D vehicles were found to meet standards.
- Of four Japanese diesels, two marginally exceeded NO<sub>x</sub> standards.

Four GM diesels--three of which were high HC emitters--and one Mercedes-Benz 300D exceeded the 0.6 g/mi particulate standard, partly as a result of high altitude testing.

One VW, three GM diesels and the one Mercedes vehicle with high particulate emissions were subjected to repair. The VW was found to have bad injectors and a dirty air filter. All three GM vehicles had injection timing maladjustments. The Mercedes diesel had some defects in the injection pump and injectors, a surprising diagnostic in the light of the fact that gaseous emissions were low. All three GM vehicles and VW showed large declines in HC emissions after repair (typically 50 percent) and a 10 to 15 percent increase in NO<sub>x</sub> emissions. All gaseous emissions on the Mercedes increased after repair by a small amount but particulate emissions declined by 46 percent. (It appears that much of the decline can be traced to replacement of a dirty air filter!)

Although opacity was measured, only the average opacity over the FTP was reported. The FTP is a lightly loaded cycle and smoke opacity is typically low over most of the cycle. On average, the opacity values for vehicles passing the FTP was 2.8 percent while the opacity for failed vehicles was 4.27 percent. However, there was considerable overlap among the measured values for individual vehicles in the two groups. We note that values below 5 percent opacity have little visual impact and even the accuracy of the smoke meter is usually 1 percent.

In-use data on heavy trucks is more limited. EEA was able to locate only one program conducted by South-West Research Institute under contract to the EPA that has tested emissions from in-use HDDV's. Data from a total of 30 vehicles (23 trucks, seven buses) were obtained from tests conducted on the chassis dynamometer. All 30 vehicles had engines calibrated to the 1.5 HC/25 CO/10 NO<sub>x</sub> gm/BHP-hr emission standards. 22 of 23 trucks met appropriate HC+NO<sub>x</sub> standards, but six of seven buses showed high HC+NO<sub>x</sub> levels relative to the standard, the average value

being 14.5 g/BHP-hr. Particulate emissions levels for buses were also four times the level for the 23 trucks in the sample. This small sample indicates that buses, in particular, may have special problems.

### 3.3 EXISTING I/M PROGRAMS FOR DIESELS

Although many states, including California, have laws that allow citations to be issued for vehicles emitting excessive smoke, only four states have adopted any form of mandatory I/M program for diesels.

The earliest to adopt such a program was Arizona, where diesel vehicles in the Phoenix area were required to be inspected annually since 1976. The inspection was required for both light-duty and heavy-duty diesels. Both types of vehicles were tested on a dynamometer, but the test type differed between the two.

For light-duty diesels, the vehicle was run on the chassis dynamometer loaded in accordance with the Clayton key-mode cycle for the higher speed. The test speed is a function of the engine size and varies from 36 mph for 4-cylinder engines to 45 mph for 8-cylinder engines. Smoke measurements were taken with the aid of an opacity chart (similar to a Ringelmann chart) and were based on visual observation of smoke after the vehicle had stabilized at steady-state cruise. Vehicles emitting smoke at a visual opacity level greater than 20 percent were failed.

Heavy-duty diesels were tested differently. Each vehicle (usually just the truck tractor unit) was mounted on a twin-roll dynamometer and the truck was accelerated to governed speed. Dynamometer load was then progressively increased until engine speed dropped to 80 percent of governed speed at wide-open throttle. Smoke was then measured using a light-extinction type smoke meter (Celesco) with the detection unit mounted on the exhaust stack. Vehicles with smoke opacity greater than 25 percent were failed on this test.

All testing of diesel vehicles in Arizona was suspended in 1980. Although the test data was recorded on tape, EEA has learned the data was never analyzed. Conversation with the Arizona I/M staff revealed that the overall failure rate (light- and heavy-duty) was under 3 percent; the low failure rate was one of the major reasons this program was suspended. No written documentation of program operation or difficulties encountered is available.

Louisville, Kentucky, began an I/M program in 1984 that includes diesel vehicles up to 18,000 lb GVW (declared GVW). The test consists of measurement of smoke opacity at idle, using a light extinction type smoke meter. Few problems crop up at idle, and the actual failure rate in 1984 for diesels is well below 1 percent.

Portland, Oregon has had an I/M program since 1976, and both light and heavy-duty vehicles are included. All light-duty diesels (up to 8,500 lb GVW) are inspected annually, and the test utilized is the two-speed idle--(idle and 2500 RPM no-load idle). Smoke opacity is measured using an opacity guide film strip (see Section 4 for details) and vehicles exceeding 20 percent opacity are failed. Because the test is conducted at no-load idle, the actual failure rate is low. Oregon does not separately analyze failure rates for diesels, but the I/M program manager, Mr. Householder, informed us that the failure rate was under 2 percent. Portland does not require inspection of heavy-duty diesels, but the law provides for police to issue citations to "excessively smoky" vehicles.

The Oregon Department of Environmental Quality has been considering a program to test buses belonging to the local transport authority, Tri-Met. In mid-July, 1984, a series of opacity tests were conducted on 172 buses from the fleet of 710 buses. Opacity was measured at idle, at "snap idle", and at "stall idle". During the snap idle test, the throttle is rapidly opened to bring the engine to maximum governor RPM and then released, with the gear in neutral. This is done three times in quick

succession and peak opacity levels are recorded. For the "stall idle", the (automatic) transmission is placed in drive and the vehicle brakes applied. The throttle is then moved to wide-open, so that the engine is running at transmission stall speed. Opacity measurements are made at this steady-state level.

The results of the testing are shown in Table 3-1 for the snap and stall idle tests only as the results of the idle test are uninteresting. The failure rate of the buses of two opacity cutpoints--13 and 20 percent are shown for both tests by engine group. The Cummins diesel and the DDA 6V-92T are turbocharged, while the 8V-71N engines are naturally aspirated. Note that turbocharged engines emit a high opacity smoke "puff" on the snap idle while their stall idle smoke may be very low. For the naturally aspirated engine, the stall idle proves to be the more stringent test with a failure rate that is 2 to 3 times as high as that on the "snap idle". The odd result at 20 percent opacity for the 1973-75 8V-71N engine is due to one malperforming engine.

New Jersey has a law that is currently not enforced, requiring that all diesel vehicles shall not emit smoke in excess of 20 percent opacity when tested on the "lug down" procedure. The procedure can be used on the dynamometer or on the road. The dyno procedure consists of:

(1) running the vehicle at governed engine speed in a gear that results in a vehicle speed of 45-60 mph, and (2) increasing the dyno load progressively until the loading reduces engine RPM to 80 percent of governed RPM. Peak smoke opacity measured over a period of 5-10 seconds is the value compared to the 20 percent cutpoint. The law merely set the test procedure but did not specify if random or periodic inspections were to be conducted using this procedure.

The road test procedure requires: (1) running the engine at governed speed in a gear that produces a vehicle speed of 10-15 mph at governed speed, and (2) using the brakes to load down the engine to 80 percent of

TABLE 3-1  
OREGON BUS TESTS

<u>Engine</u>	<u>Test</u>	<u>Failure Rate (%)</u>		<u>Model Year</u>
		<u>Opacity &gt;13%</u>	<u>Opacity &gt;20%</u>	
6V-92T (TURBO)	SNAP	25	16	1982
	STALL	8	0	
CUMMINS (TURBO)	SNAP	35	8	1981
	STALL	22	8	
8V-71N	SNAP	12	8	1977
	STALL	35	20	
8V-71N	SNAP	4	4	1975-73
	STALL	12	0	
8V-71N	SNAP	7	3	1972 REBUILT
	STALL	14	5	

Source - Oregon DEQ

governed speed. The smoke measurement is performed in a manner identical to that for the dyno procedure. Neither of those test procedures or regulations are currently actively enforced.

New Jersey also had a separate law for smoke emissions from buses. Originally, the law required a smoke measurement from all buses during an acceleration from standstill to about 20 mph. Peak smoke opacity was measured during the acceleration, and vehicles exceeding peak smoke opacity of 40 percent were failed. This law was enforced from 1971 to the late-1970's. The introduction of buses with vertical smoke stacks lead to difficulties in mounting the smoke detector, and, for such vehicles, a visual check of smoke opacity was used to enforce the law. Starting in 1982, New Jersey began using the "snap idle" test (as defined for Oregon) for buses. Smoke measurement is performed with a smoke opacity meter (Wager), and vehicles exceeding 12 percent peak smoke opacity were failed. This test procedure has been used since 1982, although it was not formally adopted as a law until December 1984. Test results from tests on 583 buses are shown in Table 3-2. Most of the older buses (to 1979) were naturally aspirated, but some of the 1980 and later buses are turbocharged. Note that the test failure rate for the 1980 and later buses is significantly higher than for the older vehicles. This can be expected for turbocharged vehicles in the light of the engineering analysis performed.

The State of Colorado is in the process of adopting new regulations for diesel smoke inspection. As of 1984, no test procedure had been formally adopted. However the state performed smoke tests using the two-speed idle, snap idle and 30 - 50 mph acceleration modes on two vehicles, one failing the FTP and the second passing the FTP--both GM Oldsmobile light-duty diesels. Only the 2500 RPM and 30-35 mph loaded mode acceleration showed substantial differences in peak smoke opacity between the two vehicles, as shown in Table 3-3. The large difference in smoke opacity at 2500 RPM is surprising as engineering analysis suggests that the differences should be much smaller.

TABLE 3-2  
NEW JERSEY SNAP IDLE TEST RESULTS  
FOR BUSES

DIESEL BUS SMOKE OPACITY SURVEY  
(12% standard applied)

TABLE 1

Diesel Bus Smoke Emissions by Model Year

<u>Model Year Group</u>	<u>Sample Size</u>	<u>% Greater Than 12% Opacity</u>
Pre-1960	7	0.0
1960-1969	201	13.4
1970-1979	306	10.8
1980 and later	69	17.4

TABLE 2

Diesel Bus Smoke Emissions by Make

<u>Make</u>	<u>Sample Size</u>	<u>% Greater Than 12% Opacity</u>
MCI	78	14.1
GM	295	12.9
Flex	171	6.4
Silver Eagle	8	37.5
Prevoise	6	33.3
Other	35	28.0

TABLE 3

Distribution of Diesel Bus Smoke Opacity Test Results

<u>Opacity Interval (%)</u>	<u>Observations</u>	<u>% of Total</u>
Greater than 50	1	0.2
Greater than 40	2	0.3
Greater than 30	4	0.7
Greater than 25	8	1.4
Greater than 20	22	3.8
Greater than 15	51	8.7
Greater than 12	72	12.3
Greater than 10	101	17.3
Greater than 5	290	49.7
Greater than or equal to 0	583	100.0

Source - New Jersey DEP

TABLE 3-3  
 COLORADO I/M TESTS ON  
 TWO GM DIESELS

	"Passed" Vehicle	"Failed" Vehicle
HC <sub>FTP</sub> (g/mi)	0.322	3.106
CO <sub>FTP</sub> (g/mi)	1.078	4.519
NO <sub>x</sub> FTP (g/mi)	1.530	0.649
Particulate (g/mi)	0.295	1.057

Peak Smoke Opacity (Percent)

Idle	2	~2
2500 RPM	12	38
Snap Idle	88	98
30-50 mph accel	35	82

Source - "LDDV Emissions at High Altitude" T. W. Hollman and  
 J. L. Gallagher, Colorado Department of Health.

Colorado State University (CSU) conducted a series of smoke opacity tests on 50 light-duty vehicles, and these tests were conducted under contract to the State of Colorado. A series of six tests were conducted on each vehicle, three tests that were categorized as "unloaded" (idle, high idle and snap idle) and three that were classified as "loaded" (40 and 55 mph cruise, and a 30-50 mph acceleration). Data from the "unloaded" tests were not available, but the report from CSU concluded that none of these tests were good indicators of smoky vehicles. The loaded tests were run by increasing dyno loading so the vehicles were at wide-open throttle.

The loaded mode tests revealed that at a cutpoint of 15 percent, the 55 mph test is the most stringent, while the 40 mph test is the least. If the cutpoint is raised to 25 percent, both the 40 and 55 mph tests fail the same number of cars but not the same cars; the acceleration test fails nearly all (except two) cars that fail either the 40 or the 55 mph test. The results are shown in Table 3-4, and suggests that the acceleration test at a 20/25 percent opacity cutpoint is an adequate test and is equivalent to the cruise mode tests. Most vehicles that exceeded the 10 percent opacity limit were "repaired" by either having their timing adjusted or by derating the power (adjustment of maximum fuel setting). A few vehicles continued to exceed the opacity cutpoints (as shown in Table 3-4) after repair and EEA suspects that those vehicles had injector problems. CSU indicated that the 40 mph was the easiest to implement of the three loaded mode tests.

The failure rate observed, even at a 25 percent opacity cutpoint, is extremely high by normal I/M standards. Part of the high failure rate can be explained as being due to the fact that these tests were performed at high altitude, where reductions in air density cause full load smoke to increase significantly. The EMA has suggested that full load smoke opacity increases approximately 4 percent for every 1000 feet of altitude for naturally aspirated engines, so that these high failure rates may not occur at low altitude conditions.

TABLE 3-4  
SMOKE OPACITY TESTS  
ON 50 DIESEL CARS

Number of Vehicles Exceeding	Test (Before Repair)		Test (After Repair)	
	<u>40 mph</u>	<u>55 mph</u>	<u>40 mph</u>	<u>55 mph</u>
15% opacity	28	35	8	13
20% opacity	23	26	6	6
25% opacity	18	18	3	3

Source: Colorado State University

### 3.4 CONCLUSIONS

There is limited data on in-use diesel vehicle emissions and these data are predominantly confined to results from FTP tests on light-duty diesel vehicles, where gaseous and particulate emissions are measured. Little information exists on smoke opacity. A review of all available in-use data reveals that:

- 1980 and later model year LDDV's are more likely to fail emission standards for California than previous model year vehicles, primarily because of the more stringent emission standards.
- Most failures of emission standards are relatively minor as emissions are typically no greater than 50 percent above standards.
- Even in the small sample available, failure patterns are evident. It appears that GM diesels have failure rates substantially higher than other makes while Peugeot and VW diesels have a much lower but still significant failure rate. On the other hand, Mercedes diesels and Japanese diesels tested have insignificant failure rates, but this result is based on a very small sample.
- The most common malperformances leading to high emissions, in the order of rate of occurrence, are: (1) EGR system or EGR valve failures, (2) timing maladjustments, and (3) injector fouling. Only the latter two malperformances cause high smoke or particulate emissions.

Available data on heavy-duty vehicles do not permit a comparable analysis, but the limited data show a very low rate of failure to meet appropriate emission standards. It must be noted that HDDV emission standards are much less stringent than LDDV standards.

A survey of ongoing inspection programs for diesels revealed three active programs, one that ended in 1980 and one that is likely to be initiated in 1985. Of the three active programs, two--Portland and Louisville--utilize idle tests for LDDV's that are not very effective and, hence, fail few vehicles. The third program, in New Jersey, is limited to buses. The "snap idle" test appears to provide some identification of smoky heavy-duty vehicles but there are observable differences in the response

of naturally aspirated vs. turbocharged engines that are not accounted for in the test program.

The now defunct Phoenix I/M program for all diesels (LDDV and HDDV) utilized a loaded-mode test that is theoretically more effective than the idle test in detecting smoky vehicles. However, the observed failure rate was low, suggesting that the percent of diesels that have smoke problems is low. However, neither the GM or VW diesel was available when the program was active. The Colorado State University test program suggests that the acceleration test (30-50 mph acceleration at WOT) may be effective in identifying smoky light-duty vehicles.

## 4. TEST OPTIONS FOR DIESEL SMOKE INSPECTION

### 4.1 OVERVIEW

The motivating factor for developing an inspection program for diesel powered vehicles is ARB's concern about the public health and visibility impact of diesels emitting in excess of applicable standards as well as public complaint against excessive smoke. At the outset of this effort, it was determined that the maximum public health impact and public exposure to diesels that are high emitters occur under city driving, where low speed stop-and-go conditions are typical. Accordingly, the inspection procedure must be designed to identify those vehicles that are excessively smoky or are high emitters under such conditions. To the extent possible, the inspection must also identify high emitters in other, less common, driving conditions. In general, inspections are of two basic types--one, where emissions are measured over a prescribed cycle and two, where engine components that are primarily responsible for controlling smoke and emissions are inspected to ensure that they have not been maladjusted or are malperforming. The first basic type encompasses a wide variety of test cycles and smoke measurement methods and this type is of interest to the CARB as it is consistent with the prescribed test for gasoline powered vehicles.

In this section, these two test types and the different available options that CARB can choose to implement are examined in detail, for both light-duty and heavy-duty diesels. Under the first type, we have considered the method of measuring smoke opacity separately from the issue of test cycle; the analyses of these topics are presented in Section 4.2.1 and 4.2.2 respectively. In Section 4.3, potential component inspection programs and or mandatory maintenance programs are addressed.

## 4.2 TESTS FOR SMOKE OPACITY

### 4.2.1 Measurement of Smoke Opacity

Most field enforcement of smoke emissions today is done visually. Visual methods suffer from the inherent inconsistencies of judgement, although procedures are available to reduce or minimize such inconsistencies. More recently, portable smokemeters for field use have become available that are likely to provide more accurate and consistent measurements than visual techniques. Naturally, the use of smokemeters adds objectivity to the inspection but may also entail difficulties in mounting the detector unit at an appropriate location.

Visual measurements of smoke are simple to perform as no special equipment is needed. The simple, unaided visual observation of smoke for a subjective determination of excessive smoke emission is widely used by many states with laws to empower police to issue a citation for excessively smoky vehicles. To make proper smoke observations, the observer should be positioned off to the side of the road about 30 to 50 feet from the roads' centerline so that his/her line of sight is perpendicular to the motion of the vehicle. This will minimize the "tunnel effect" of looking down the length of smoke column and gives a more accurate judgement of the smoke opacity. Advantages of this procedure are:

- it is simple to implement
- it correlates with public perception of smoke
- it requires no new regulatory initiatives by the CARB

The observer should concentrate on the area immediately behind the exhaust stack rather than consider the entire plume. For the best conditions, the observer should have the sun at his back and the background (behind the truck) should be clear and consistent.

The two most common methods for visual comparisons of smoke density to a "standard" are the Ringelmann Smoke Chart and the Opacity Guide System.

#### The Ringelmann Smoke Chart - Printed Gray Shades

The Ringelmann Smoke chart, as published by the Bureau of Mines in their Circular 8333, was developed by Professor Maximilian Ringelmann of Paris, France in the late 1800's. It was originally developed as a guide for operators to adjust excess air for blast furnace smelting efficiency. This chart has been the primary enforcement tool in this country since the early 1900's.

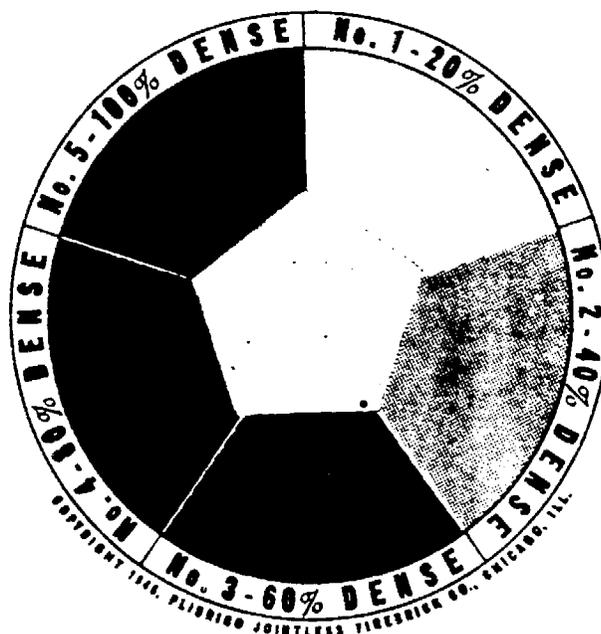
The Ringelmann system uses a chart of graduated shades of gray produced by varying the width of cross-hatched black lines on a white background. The line widths are varied so that the black occupies approximately 20 percent, 40 percent, 60 percent, and 80 percent of the total area of the chart. These shades are referred to as Ringelmann Nos. 1, 2, 3, and 4. A solid black is Ringelmann No. 5. An example is shown in Figure 4-1.

The Ringelmann rating system usually requires the observer (after being properly trained on a stationary stack) to be able to retain in his mind certain opacity levels. He then is required to correlate this mental picture to observations of various smoke levels made under a variety of lighting and background conditions. This measurement technique is difficult, especially on a moving vehicle. However, trained observers have been found to give consistent readings under standardized light conditions.

Various pocket-sized Ringelmann Charts have been developed for field enforcement work. The EMA has objected to their use because it has found these charts to be inconsistent in density. In addition to this, the observer is forced to compare the plume to the chart with the chart receiving light from an entirely different portion of the sky, i.e., the

FIGURE 4-1

CALIFORNIA HIGHWAY PATROL  
SMOKE CHART  
RINGELMANN TYPE



INSTRUCTIONS

1. The scale should be held at arm's length at which distance the scale will blend into uniform shades.
2. Then compare the smoke (as seen through the hole) with the chart, determining the shade in the chart most nearly corresponding to the shade or density of the smoke.
3. A motor vehicle shall be considered to be emitting "excessive" smoke, gas, oil or fuel residue if on visual comparison for a reasonable period the exhaust products have a density that is equal to or greater than No. 2 (40%) on the Ringelmann Chart.  
Observer should not be less than 100 feet nor more than 500 feet from the vehicle.  
Observer should avoid looking towards bright sunlight.

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chart receiving light from behind and reflected to the observer, and the smoke being lighted by the sky in front of the observer.

#### Opacity Guide System - Film Strips

The Opacity Guide uses a translucent material (usually a photographic film strip) of graduated steps of opaqueness to smoke emission density. Its advantage over Ringelmann charts is because the opacity of a smoke plume and the Opacity Guide are observed and compared simultaneously--with the same lighting conditions and background. The observer holds the guide at about arm's length as he sights it on the smoke plume. The opacity rating is then determined by comparing the smoke plume to the graduated density on the film strip guide.

The State of Oregon has developed such a guide for their "Motor Vehicle Visible Emission" regulation. The guide is composed of different segments of silver density filter film. The segments block 10.9, 20.5, 39.8, and 60.2 percent of the light that falls upon it. These segments are labeled 10, 20, 40, and 60 percent opacity. The guide can be purchased from The Department of Environmental Quality, State of Oregon.

The Opacity Guide System is superior to the Ringelmann Chart for judging opacity. There is some concern, however, about the degree of correlation between the Opacity guide System and an opacity type smokemeter. The correlation appears to be biased at opacity readings above 20 percent when the response rate between the human eye and the smokemeter lead to differences in judging puffs of smoke.

Many state and local agencies have regulations based upon the Ringelmann Smoke Chart. However, the federal regulation for heavy-duty trucks is based on an opacity measurement system. There has been a tendency to equate these two systems without considering their differences. Many regulations now in force regard the two systems as equatable, but the

two systems may not equate. For example, Ringelmann No. 1 is not usually equal to a 20 percent opacity and Ringelmann No. 2 is not usually equal to a 40 percent opacity.

The use of the Ringelmann Smoke Chart or Opacity Film Strips must provide allowances for such inequalities by allowing some margin over the Federal certification procedure opacity level. Ideally, either system can be used in a test area with standardized background lighting for the purposes of an inspection program. Such a visual determination is likely to correlate well with an opacity measurement. The advantages and disadvantages of visual tests are summarized in Table 4-1.

Instrumented measurements of smoke opacity provide an objective and respectable measurement that can be used for consistent measurements. Two basic types of smokemeters are available, the Bosch type and the light extinction type. The number of models of smokemeters available are few and EEA contacted all current smokemeter manufacturers to obtain price/performance information.

The Bosch smokemeter consists of two separate units--a sampler and an evaluation unit. The sampler is a spring loaded suction pump that must be cocked prior to sampling. Release of the trigger leads to a small sample of the exhaust being sucked into the sampler through a filter paper. The exhaust can be sampled at any point desired, including from within the exhaust pipe. Smoke particles as well as heavier hydrocarbons are trapped in the filter paper, changing the papers color from white to a shade of gray that is dependent on smoke opacity. The evaluation unit is a photocell detector device that reads the "greyness" of the filter paper in Bosch smoke number units.

The Bosch smoke numbers have been found to correlate better with particulate emissions than with smoke opacity and are often used for simple approximate measures of particulate emissions, which is also of concern

TABLE 4-1  
 SUBJECTIVE SMOKE OPACITY MEASUREMENTS METHOD

<u>TEST TYPE</u>	<u>METHOD</u>	<u>ADVANTAGE</u>	<u>DISADVANTAGE</u>
UNAIDED VISUAL	OBSERVATION OF BLACK SMOKE	"GROSS" EMITTERS CAN BE CAUGHT WITH NO INSTRUMENTATION AND NO NEW REGULATIONS	NO CONTROL OF PASS/FAIL CRITERIA
RINGELMANN CHARTS	COMPARISON OF SMOKE AGAINST COLOR CHART	INTRODUCES SOME DEGREE OF CONTROL ON PASS/FAIL CRITERIA	PASS/FAIL CAN VARY DEPENDING ON BACKGROUND LIGHT, VEHICLE SPEED, AIR MIXING
FILM STRIPS	COMPARISON OF SMOKE AGAINST NITRATE TRANSPARENCIES	CONTROL FOR VISUAL BACKGROUND, EASIER TO COMPARE THAN RINGELMANN CHART	CONTROL OF VEHICLE SPEED, AIR MIXING STILL NECESSARY

to the CARB. Other advantages of this smokemeter include the fact that sampling is easy, no delicate electronic or optical components are exposed to exhaust, and a permanent record of this measurement is available on the filter paper. (The filter paper does degrade with time when stored).

Disadvantages of the Bosch smokemeter are that the measurement does not correlate well with perceived smoke opacity. The smoke is sampled for a small interval of time (approximately 1 second) and therefore, it can be used to measure smoke only on steady-state tests after the engine is stabilized and smoke emissions are relatively constant. Finally, its use will require some research effort to identify appropriate pass/fail cutpoints in Bosch smoke numbers.

The light extinction type of meter is more commonly used for smoke opacity measurement, and consists of a sensor unit and an indicator unit. The sensor unit contains a light source and an optical detector device supported in a yoke assembly. Typically, it uses solid state LED's and photodetectors which are resistant to vibration and shock. When the light beam crosses the smoke plume, any reduction in light transmittance is measured as opacity, or the percent of light blocked. The indicator unit contains the controls, meter for opacity, electronics and power supply.

The PHS smokemeter, specified for the Federal smoke test procedure for HDD engines, uses an incandescent light source that is collimated with a lens to a beam of 1.125 inches in diameter, and a detector whose sensitivity is restricted to the visual range, comparable to that of the human eye. The unit is available from South-West Research Institute, but is apparently no longer being produced, except on special order.

Two other meters operating on essentially the same principle as the PHS meter, but using a green light emitting diode as the light source are manufactured by Celesco and Wager. Both devices are isolated from

excessive exhaust contamination by being outside of the exhaust plume, but manufacturers' literature says this optical devices (lenses, light source and detector) must be cleaned periodically to prevent any gradual soot buildup as some contamination from exhaust is unavoidable. The sensor unit can be clamped on to the exhaust outlet so that the unit is perpendicular to the exhaust plume and the light penetrates through the center of the plume before reaching the detector. Both the Celesco and Wager units are available as portable models. For heavy-duty trucks, the Federal smoke test procedure specifies that opacity must be measured  $5 \pm 1$  inch from the exit of the exhaust pipe.

Advantages of this type of unit is that smoke opacity can be measured with relatively good accuracy under any ambient condition (the light source is pulsed to eliminate interference with ambient light). Measurements provide data on instantaneous smoke opacity, and this can be recorded on a chart recorder to obtain instantaneous, peak or average opacity values during both steady-state and transient cycles. Disadvantages of this unit arise from the requirement to clamp the unit near the exhaust outlet (which, on heavy-trucks, may be difficult to access). The units may suffer from problems with condensation, soot buildup and thermal draft. All of these disadvantages can be fairly easily overcome with proper usage of the instrument.

Data on all available smokemeters including the January 1985 price is provided in Table 4-2.

#### 4.2.2 Test Cycles

Because of the fundamental differences in operating modes and in failure modes between light-duty and heavy-duty vehicles, the choice of test cycle for each vehicle type is considered separately.

The analyses presented in Sections 2 and 3 of this report indicate that, for light-duty vehicles, the most important malfunctions leading to high smoke are:

TABLE 4-2  
SMOKEMETER FEATURES AND FUNCTIONS

<u>Manufacturer</u>	<u>Model</u>	<u>Portable*</u>	<u>Measurement Method</u>	<u>Base Price</u>
Robert Bosch, GMBH	EFAW65	yes	Filter Color	\$1860
Telonic Berkley, Inc.	107	no	Light extinction (green)	n.a.
"	200	yes	" "	\$2420
Southwest Research Inst.	PHS	no	Light extinction (incandescent lamp)	\$3600 + 375 for filters
Robert H. Wager Co.	P6P	no	Light extinction (green)	\$2950
"	650	yes	" "	\$2000

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\*All models are portable to some degree, but only those that are powered by their own batteries or by the vehicle power supply and can be mounted for mobile testing are designated portable.

- Maladjusted fuel injection timing
- Injector clogging or leaking
- Injection pump maladjustment (of full load fuel)
- Engine piston/valve related defects

Various modes are considered in the light of their ability to detect these malperformances.

The idle mode is a no load condition with very high excess air in the combustion chamber. Only vehicles with serious defects such as leaky pistons and valves, or a damaged injector(s) will fail this mode. Even at a stringent 10 percent opacity pass/fail cutpoint, current experience shows that less than 1 percent of vehicles will fail this test.

The 2500 RPM idle is only a slightly more stringent test than the idle test. Since there is no easy way to measure RPM on a diesel, this test mode is more aptly titled the high speed idle mode. In general, it will uncover defects similar to those identified by the idle test, as well as malfunctions of the timing advance mechanism in the injection pump. Current experience in Portland suggests that a failure rate of 1 percent for this test is likely.

The snap idle test, which involves rapidly depressing the accelerator and then releasing it when engine reaches governed speed, is based on peak smoke opacity. The test can, in theory, detect most of the important malfunctions in LDDV's. However, most engines accelerate from idle to governed speed ( with the gear in neutral) in less than 1 second. As a result, the smoke puff is of extremely short duration and it is not clear that even a well-maintained car will not emit a short-duration "puff" under such highly transient conditions. Data suggests that even vehicles in good condition can emit a high opacity puff during the snap idle.

The loaded mode cruise test is expected to be effective, if the test is performed at 50 mph, in detecting most major malfunctions of diesel engines. Since the test is run at steady-state and moderate loads, it will not detect maladjustment of the full-load fuel stop, or transient air-fuel ratio control problems that may occur especially on turbocharged vehicles. Additionally, any problems with the injector timing advance unit may result in low-speed smoke that is not present at higher speeds. This test can be performed either on the test track or the dynamometer. However, at 50 mph, the test track will have to be fairly long--approximately 2000 yards--to obtain a good steady-state test measurement of smoke opacity. A loaded-mode test at 50 mph on the dynamometer is used by some states in their I/M program for gasoline powered vehicles, and hence is not difficult to implement.

The lug-down procedure requires that a vehicle be mounted on the dynamometer and driven in a gear such that maximum speed at wide-open throttle (WOT) is about 50-60 mph. Dyno loading is gradually increased until speed drops by 15-20 percent and smoke opacity is measured in this mode. Because the engine will be running at near peak horsepower output, the stresses on the engine, transmission and tires will be very high. EEA does not recommend this test for light-duty vehicles due to liability considerations in case of tire/transmission failure.

The acceleration test requires that the vehicle be accelerated from rest (or very low speed) at wide-open throttle for  $7(\pm 1)$  seconds and smoke opacity be measured during the entire acceleration. Maximum average opacity is defined as that value of opacity not exceeded for more than 1 second during the acceleration. (This is to allow for an instantaneous puff of smoke during the transient). The acceleration mode is very useful, because in 6 or 7 seconds the vehicle will accelerate from 0 to 30/40 mph covering the entire range of speeds encountered in city traffic. This mode addresses all major malfunctions for LDDV's that EEA has documented. In addition, the test can be performed on the test track in a

relatively short space--100 to 150 yards--or on the dyno. The dyno procedure on a vehicle with "bald" tires may give rise to tire slip on high powered rear-wheel drive diesels, but only the Mercedes 300D turbo-diesel vehicle fits in this category. (It seems unlikely that any significant number of Mercedes vehicles will have bald tires). Pass/fail cutpoints can be based on both the instantaneous peak opacity and the maximum average smoke opacity or just on the latter measurement.

The advantages and disadvantages of each test mode are summarized in Table 4-3.

The analysis of heavy-duty diesels in Section 2 showed that manufacturers believe the following to be the most common forms of HDDV malperformance:

- Disconnection of the smoke-puff limiter or maladjustment of the air-fuel ratio control
- Maladjustment of the full-load fuel screw or increasing governed speed.
- Injector fouling or mismatch
- Rebuilding without control of critical parts

It should be noted that HDDV's are normally operated at or near full load conditions and a very large percentage of trucks above 20,000 lb GVW are turbocharged. Turbocharged vehicles, in particular, have smoke emissions that are sensitive to the setting of the air-fuel ratio control or maladjustment of the smoke puff limiter.

Since HDDV's see much operation at high load, neither the idle test or high idle test are very meaningful in this context and need not be considered.

The snap idle test is unlikely to provide meaningful results, since most trucks are turbocharged. Since the turbocharger never builds boost on this test, the full load fuel settings or injector/turbocharger match

TABLE 4-3  
LDDV TEST MODES

<u>TEST</u>	<u>METHOD</u>	<u>ADVANTAGES</u>	<u>DISADVANTAGES</u>
SNAP IDLE	STARTING IN IDLE NEUTRAL GO TO WOT TILL GOVERNED SPEED IS REACHED, THEN RETURN TO IDLE (MEASURE <u>PEAK SMOKE OPACITY</u> )	EAST TO IMPLEMENT MAY UNCOVER SERIOUS PROBLEMS WITH INJECTION SYSTEM	POOR CORRELATION WITH FULL-LOAD SMOKE. CUT- POINTS DIFFICULT TO ESTABLISH
NORMAL IDLE OR HIGH IDLE	MEASURE SMOKE OPACITY AT IDLE AND/OR HIGH IDLE	CAN INCORPORATE INTO EXISTING I/M	POOR CORRELATION WITH FULL-LOAD OR TRANSIENT SMOKE
LOADED MODE CRUISE (50 MPH)	ADJUST DYNO HP SO THAT VEHICLE RUNS AT MODERATE TO HIGH LOAD	SPOTS COMMON DEFECTS IN MOST LDD'S	LOW SPEED, TRANSIENT SMOKE PROBLEMS MAY BE UNDETECTED. REQUIRES DYNO AS TRACK TEST IS DIFFICULT
LOADED MODE ACCELERATION (30-50 MPH)	ACCELERATE FROM REST AT WOT ON DYNO/OR TRACK FOR 6 ± 1 SECONDS. MEASURE PEAK AND AVERAGE SMOKE OPACITY	SPOTS COMMON DEFECTS IN BOTH CRUISE AND TRANSIENT MODES. EASIER TO PERFORM THAN LOADED MODE CRUISE	CUTPOINTS TO BE SELECTED CAREFULLY, MAY REQUIRE TURBO/NON-TURBO DIFFERENTIATION

(for rebuilt engines) are not checked. However, the test may identify the most common type of maladjustment, that of the smoke puff limiter/air-fuel ratio controller. Even for this maladjustment, the appropriate choice of cutpoints is difficult. Federal regulations permit peak smoke opacity levels of 50 percent, and, at this level, it is likely that few HDDV's will fail the test. Test on New Jersey buses show that only one bus of 583 tested exceeded the 50 percent opacity level. New Jersey has implemented a 12 percent opacity cutpoint that resulted in 72 of 583 buses exceeding this number. The legality of such an action across the board for all trucks is questionable in the light of Federal regulations permitting high opacity smoke puffs.

The stall idle test can be used only with vehicles using an automatic transmission. This involves placing the transmission in drive and going to wide-open throttle, ensuring that the brakes are applied to prevent vehicle motion. This results in the engine operating at converter stall speed, which is approximately at peak torque speed, and this is a representative RPM to conduct an opacity check. However, there is no check of the most common malfunctions, that of the smoke puff limiter or air fuel ratio control. The Oregon bus tests suggest that a 20 percent opacity limit may be appropriate. The major disadvantage of the test is that it can be used only for HDDV's with automatic transmissions; since most city buses are equipped with automatic transmissions, this may be a good check for just the bus fleet, which is also predominantly naturally aspirated.

The lug-down test can be performed on the dyno or track. On the dyno the engine is allowed to reach governed speed at wide-open throttle. Dyno horsepower is then steadily increased until the engine reaches peak torque RPM or 60 percent of rated speed, whichever is higher. This speed usually corresponds to the highest fueling rate per stroke, and a check here can reveal any tampering or maladjustment of the full-load fuel setting and in some cases, of the governed speed. The same test can be

run on the track, by selecting a gear so that the vehicle travels at approximately 15 mph at governed speed and then using the brakes to slow the vehicle to 10 mph while operating at full throttle. As with the stall idle check, this check will not identify vehicles where the air-fuel ratio control or smoke puff limiter is tampered with.

The acceleration test requires that the vehicle be accelerated from rest (or very low speed) at WOT for  $7 \pm 1$  second. On a vehicle with a manual transmission, an appropriate gear must be selected so that governed speed is not reached until the end of this period. Such a test is ideally suited to detect all of the major malperformances listed and has the additional advantage of being essentially similar to the Federal smoke test acceleration mode. As with the LDDV, the smoke opacity must be monitored over the entire acceleration mode, and peak as well as the maximum average opacity (as defined for LDDV's) must be monitored. The Federal standard requires that average opacity must not exceed 20 percent; EEA recommends a maximum average opacity cutpoint of 25 percent for consistency with Federal regulations. Peak opacity may also be controlled, if necessary.

All tests for HDDV's are summarized in Table 4-4. It is important to note that all of the conclusions expressed above for both LDDV's and HDDV's are derived from limited data and apply only to fully warmed up vehicles. In particular, most of the test modes examined for HDDV's have never been qualified with extensive field testing, so practical problems may arise in their implementation.

#### 4.3 COMPONENT INSPECTION

##### 4.3.1 Objectives

Vehicle inspection programs are of two types. In the first, all vehicles must report at a central facility that performs only the inspection, and vehicles failing the inspection must be repaired elsewhere and

TABLE 4-4

OPACITY TESTS - HDD

<u>TEST</u>	<u>METHOD</u>	<u>ADVANTAGES</u>	<u>DISADVANTAGES</u>
SNAP IDLE	AS FOR LDD	AS FOR LDD	CHOICE OF CUTPOINTS DIFFICULT. MAY IDENTIFY MALADJUSTED SMOKE PUFF LIMITER
STALL IDLE	WITH PARKING BRAKE ON, GO TO WOT WITH AUTO TRANSMISSION IN DRIVE	DETECTS SEVERAL COMMON MALPERFORMANCES CAUSING HIGH SMOKE	AUTO TRANSMISSIONS ONLY, DOES NOT DETECT MOST COMMON MALADJUSTMENT ON TRUCKS
DYNO/TRACK			DIFFICULT TO IMPLEMENT
LUG-DOWN TESTS	USING BRAKES (OR INCREASED DYNO LOADING), REDUCE ENGINE SPEED TO 60 PERCENT OF GOVERNED SPEED AT WOT	AS ABOVE, CORRELATES WITH FEDERAL SMOKE CYCLE LUG MODE	ESPECIALLY FOR TRACTOR/TRAILERS. DOES NOT DETECT MOST COMMON MALADJUSTMENT ON TRUCKS
VEHICLE ACCELERATION FOR 6 SECONDS AT WOT ON DYNO OR TRACK	ACCELERATE VEHICLE FROM REST OR LOW SPEED FOR 7 SECONDS AT WOT. SELECT APPROPRIATE GEAR SO THAT GOVERNED SPEED IS NOT REACHED	DETECTS ALL COMMON MALPERFORMANCES; CORRELATES WITH FEDERAL SMOKE CYCLE ACCELERATION MODE	MAY BE DIFFICULT TO IMPLEMENT ON DYNO. AVERAGE OPACITY OVER ACCELERATION MAY REQUIRE CHART RECORDER

recertified. The central facility usually handles a high volume of vehicles and the time for inspection is typically only a few minutes per vehicle. In the second, vehicles can be inspected at any of a relatively large number of licensed private facilities that typically perform both the inspection and (for vehicles that fail the inspection) the repairs as well. In this case, the time for inspection may be longer and the inspection more thorough. In this report, the two inspection programs are referred to as centralized and decentralized programs, respectively.

The inspection of components that control smoke in diesel engines can be a viable alternative to a smoke emission inspection program, and is particularly well suited to a decentralized program to control diesel smoke emission where the inspection time per vehicle can be as long as an hour. Most inspection/maintenance programs impose a repair cost limit that allow inspection and adjustment of relatively few components on the engine. If the smoke emission measurement phase of the program is removed and the vehicle owner can directly have those components inspected and repaired as necessary, cost and time savings accrue to the public. Alternatively, in a centralized program that directly inspects components--rather than smoke emissions--vehicles failing the inspection are automatically provided with useful diagnostic information. In this section, inspection methods for various components of interest are considered and their feasibility commented on. Because of substantial differences in malperformance modes, light-duty and heavy-duty vehicles are treated separately.

#### 4.3.2 Light-Duty Vehicles

For light-duty vehicles, maladjustments of importance are:

- Dirty air filter
- Injection timing maladjustments
- EGR system failures
- Tampering of injection pump settings

In the future, problems with the trap and associated regeneration mechanisms may occur.

Inspection of dirty air filters is trivial and can be easily performed on all vehicles by mechanics. It can be inspected at a centralized inspection station as well.

Injection timing is usually adjusted by rotating the entire pump assembly, much as the distributor assembly is rotated for setting the ignition timing on gasoline engines. In order to check the timing, a light sensitive diode is now available that can fit into the glow plug port. The diode measures the start of combustion (assumed equal to the start of injection) and flashes a strobe light that can be used to measure the timing, much as the spark plug discharge is used to tune the gasoline engine. This method is available for GM engines only, and the equipment is not interchangeable with other engines as glow plug port sizes are not standard. However, EEA has learned that adapters for other popular engine types may be available soon. The current practice for VW and Mercedes requires a special dial indicator tool that measures the pump stroke on the injection pump and must be specially inserted into the pump. This process is far more time consuming than the photodiode method and cannot be used in an inspection lane, but is a normal service item performed by most diesel mechanics.

EGR inspection is relatively straightforward and is almost identical to the method used to inspect the EGR valve for gasoline engines. The method is to disconnect the vacuum hose to the EGR valve and apply an external vacuum to the valve. On releasing the external vacuum, the valve will shut audibly. (If the valve remains open, it leads to a high smoke condition). The vacuum supply to the EGR valve can be easily checked by using a vacuum gauge and running the engine at high idle. However, this check is not required for smoke but only for NO<sub>x</sub> emissions.

Injection pump checks are more difficult to implement easily, because of the variety of pumps available as well as the difficulty in telling if the pump is maladjusted. In-use surveys have shown that maladjustment of these settings are not common. However, the full-load fuel stop on the Roosa-Master and the high-idle stop on the Bosch VE pump can be easily maladjusted for high performance. Figure 4-2 and 4-3 show the location of these stops on the two pumps respectively. The stops are factory sealed and if the seal is broken, there is good reasons to suspect tampering. However, this is not a functional check and there are legitimate reasons to adjust these stops. Manufacturers have informed us that if the adjustments are made by dealers, they are provided with tools to reseal the settings. Hence, a check to see if these seals are broken can be used as criterion to see if further inspection is required.

The inspection of traps must be based solely on engineering analysis as the first trap equipped vehicle was introduced in 1985 and in-use problems are still unknown. All evidence to date suggests that a back pressure check on the trap at high idle is probably the best check for function. An excessively high back pressure would indicate that the trap is plugged or the regeneration system is malfunctioning, while a very low pressure would indicate some breakdown of the trap due to thermal or structural damage. The Mercedes is provided with a pressure tap and it is likely the other manufacturers will follow suit. Lack of data prevents EEA from suggesting any pressure levels as cutpoints for the inspection.

#### 4.3.2 Heavy-Duty Vehicles

The discussion presented in Section 2 of this report showed that there are significant differences between the fuel injection systems used by the different manufacturers of heavy-duty diesel engines. Moreover, the engines themselves are large and can be difficult to access easily in "cab-over" trucks. Accordingly a centralized component inspection plan does not appear feasible but a decentralized, dealer supported inspection program may be possible.



# DB2

diesel fuel injection pump

FIGURE 4-2

LOW IDLE  
SPEED

FULL LOAD  
FUEL STOP

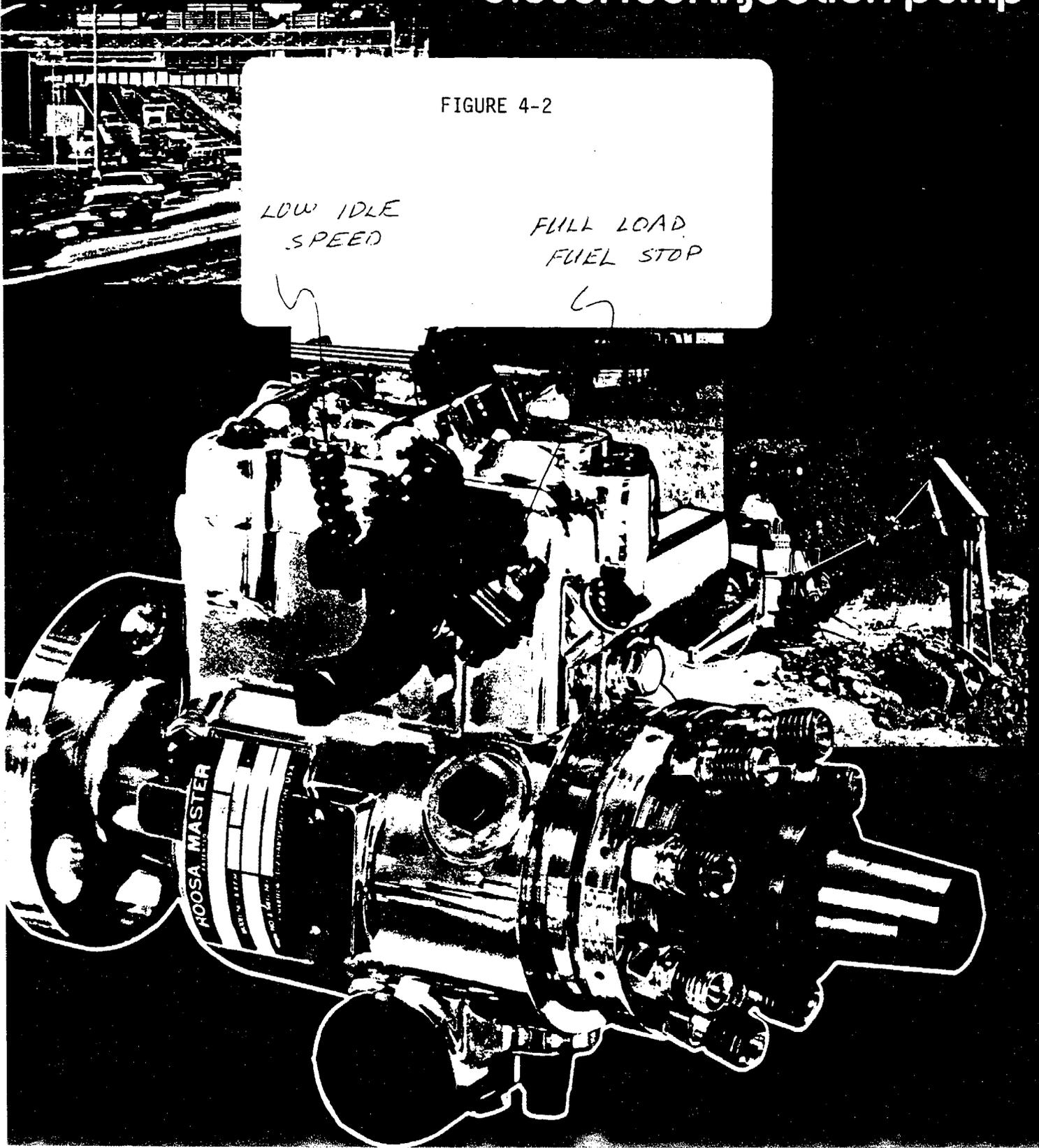


FIGURE 4-3

# ROBERT BOSCH Model VE

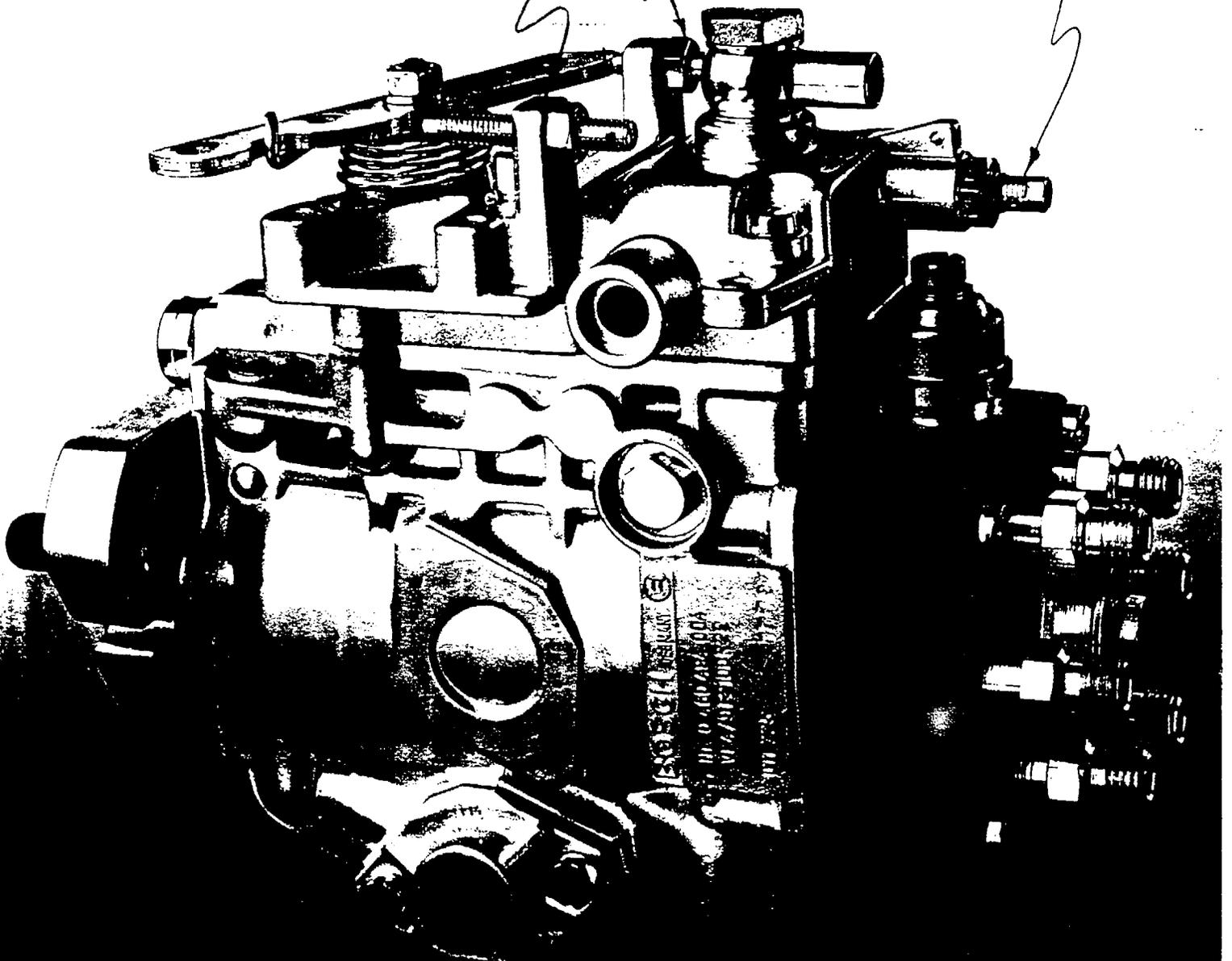
## Distributor

Compact, Versa

HIGH IDLE  
SPEED

LOW IDLE  
SPEED

FULL FUEL  
STOP



In Section 2, the following malperformances were ruled as likely in heavy-duty trucks:

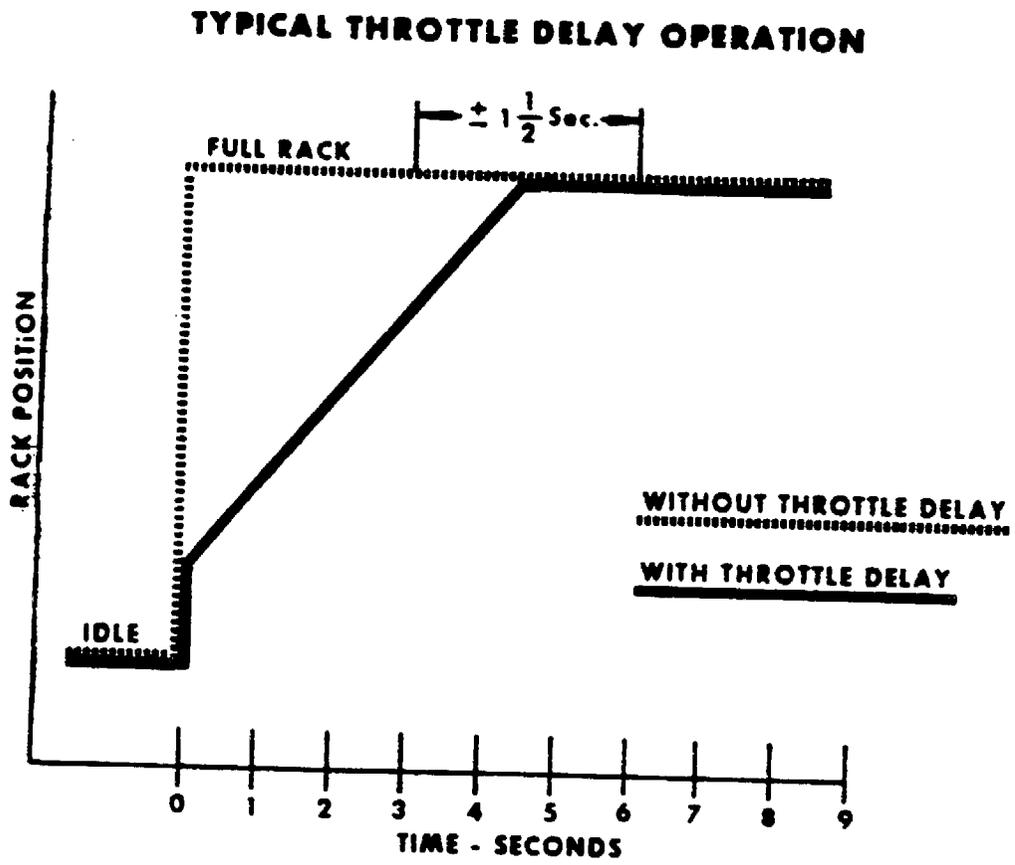
- Maladjustment of the smoke puff limiter on air-fuel ratio control
- Maladjustment of the engine governed speed and/or maximum fuel condition
- Maladjustment of the engine "overhead" in DDA or Cummins engines
- Injector fouling
- Inlet/exhaust restrictions
- Rebuild practice

The discussion of inspection of these malperformances is limited due to the time and resource constraints of this effort.

Inspection of the smoke-puff limiter or air-fuel ratio control is relatively easy. In DDA and Caterpillar engines, these devices essentially limit rack-travel until the turbo boost is fully provided to the engine. Although a specification check may be time consuming, disablement of this device is easy to check by observing the rack position and its limit on a sudden transient. In some cases, the entire unit is removed from the engines and its absence can be easily spotted. The effect of the smoke-puff limiter on DDA engines during a transient is shown in Figure 4-4. In Cummins engines, the control is implemented by bleeding rail pressure to the injector feeds until inlet boost is achieved; Cummins has informed us that an easy check would be to monitor rail pressure during a sudden transient acceleration and check against specifications.

Checking engine governed speed is also relatively easy and can be performed by depressing the accelerator to WOT and measuring the governed speed under no-load conditions. (As a screening criterion, the governor speed setting cover can be examined for tampering). This governed speed can be compared to manufacturer specifications for the

FIGURE 4-4



Source: DDA

engine. Checking the full-load fuel stop is more difficult, but a seal tampering inspection may be used as a screening criterion for further checks. Such checks would require removing the pump and measuring its fuel flow on a pump-stand, a time consuming operation.

The engine overhead adjustment on DDA and Cummins engines is another source of possible maladjustment. On Cummins engines, the rocker arm for the injector should be checked for "lash". On DDA engines, this lash check should be coupled with a check on the control lever adjustment for the unit injectors and their connection to the throttle link. These checks are expected to be quite time consuming.

Injector fouling is a difficult item to inspect for as it requires removing individual injectors and checking their spray pattern. Since manufacturers are of the opinion that serious defects of the injector will cause significant performance deterioration, such an inspection may not be necessary as repair of defective injectors is likely under normal circumstances.

Inlet/exhaust restrictions can be checked easily, as it consists of an inlet air depression check and an exhaust back pressure check. Many trucks are equipped with an inlet air depression meter to warn of a dirty air filter. The exhaust back pressure check is not used currently, but many became commonplace after traps are introduced on trucks (see discussion for LDDV).

Checking rebuild practice is not possible except by monitoring or licensing engine rebuilders to ensure that the "critical parts" list is faithfully followed. Confirmation that combustion chamber and fuel injection parts are within specification is not possible within any reasonable time limits.

In summary, it appears that there are several common malperformances that can be easily checked for, but the time required and detail differences between trucks suggest that a decentralized dealer based inspection be implemented.

## 5. RECOMMENDATIONS AND VALIDATION

The analyses performed by EEA shows that it is possible to implement either a centralized or decentralized inspection and maintenance program to identify and repair diesel vehicles with high smoke emissions. However, the benefits of the program are difficult to quantify as there is no data on the distribution of smoke opacity as measured on the recommended test procedure for a sample of light-duty vehicles. A pilot program or random tests of diesel vehicles can easily provide the necessary data for a quantification of program benefits. In general, a reduction of smoke also results in a reduction of HC and particulate emission.

For light-duty vehicles, EEA recommends that the low-speed wide-open throttle acceleration test be implemented and smoke opacity be measured using a light extinction type smokemeter to measure smoke opacity. The test is formally described in Table 5-1. EEA has also provided some recommended cutpoints for maximum average smoke and peak smoke during the test, but the ARB may wish to adjust the cutpoints after some samples of California diesels have been tested.

The ARB has also requested that a method to inspect the EGR system be provided. This is included in Table 5-1, but it must be noted that this procedure is not required for controlling smoke emissions.

EEA recommends an essentially similar test for all heavy-duty vehicles. The only other considerations are:

- An appropriate gear must be chosen so that governed speed is not reached during the 7 second acceleration test
- The smokemeter light beam must intersect the exhaust plume 5 ± 1 inch behind the plane of the exhaust pipe exit
- Opacity pass/fail cutpoints be adjusted to 25 percent for maximum average opacity and 40 percent for peak opacity.

TABLE 5-1  
INSPECTION PROCEDURE  
FOR LIGHT-DUTY DIESEL

**Note** - Engine should be totally warmed up for test.

**Tools required** - one portable smoke opacity meter, light extinction type  
(either Celesco or Wager)

**Step 1:** Ensure that smoke meter is warmed up (switch on for 15 minutes before test). Attach detector to exhaust pipe so that:

- detector is perpendicular to exhaust pipe outlet
- centerline between light-source and detection device on detector is aligned to exhaust center line
- detector center line is 1 1/2 to 2 inches away from exhaust outlet

Ensure that the exhaust pipe clamp is tight. Meter unit should be placed inside vehicle.

**Step 2:** Vehicle can be on dynamometer or open-road. If on dynamometer, ensure that vehicle is restrained from moving forward. Start engine and, after 5 seconds, accelerate engine in neutral to maximum speed (governed speed) by pressing accelerator pedal to floor, and removing foot when engine hits governed speed. Repeat three times in quick succession. This step ensures that any accumulated particulate is blown out from exhaust.

**Step 3:** Set meter to read instantaneous opacity values (i.e., **not** in "peak hold"). Place vehicle in drive (for automatics) or in 2nd gear for manuals. Accelerate with gear engaged at wide-open throttle, starting from rest or 2-3 mph, for  $7 \pm 1$  second. Observe smoke opacity reading throughout acceleration.

TABLE 5-1 (cont'd)

**Step 4:** Peak opacity reading is defined as the highest instantaneous reading observed. Maximum average opacity is defined as the value of opacity not exceeded for at least 5 seconds out of 7 seconds during the acceleration. Vehicle fails test if:

Peak reading exceeds 30 percent opacity

Maximum average reading exceeds 20 percent opacity

(These cutpoints are recommended by EEA but may be adjusted to increase or decrease inspection stringency factor.)

#### EGR SYSTEM CHECK

- o With engine off, disconnect vacuum hose to EGR valve and connect vacuum pump. Apply vacuum to EGR valve, then release quickly. If EGR valve is OK, valve should shut audibly when vacuum is released.
  
- o With engine running (and fully warmed up), disconnect EGR vacuum hose. Raise engine speed to hi-idle and check for presence of vacuum at hose. If no vacuum is present, electronic vacuum modulator is defective, or vacuum hose is defective.

As an option, the ARB can consider a decentralized program where components whose malfunctions that we have determined are the major causes of excessive smoke emissions are inspected.

For light-duty diesels we recommend that the following be inspected:

- Intake air filter
- Injection timing
- EGR system
- Injectors
- Anti-tampering seals on fuel injection pump

The inspection methods for some of these components vary by make and model (as discussed in Section 4). Table 5-2 provides a summary of the method and the typical time required for inspection.

For heavy-duty trucks we recommend inspection of:

- Intake air cleaner
- Smoke-puff limiter or air-fuel ratio control
- Governed speed
- Anti-tampering seals on the fuel injection pump
- "Overhead" adjustment (for DDA and Cummins engines)

The component inspection programs are expected to essentially achieve the same ends as the smoke inspection, i.e., repair those malfunctioning components that lead to high smoke.

The ARB had also requested an evaluation of the effect of the \$50-\$100 repair cost limit for LDDV's. Based on a survey of Washington, D.C. area diesel dealership service departments, the following costs can be considered as appropriate averages:

- Inspection and replacement of dirty air filters costs about \$5-\$8.

TABLE 5-2  
COMPONENT INSPECTION METHODS

<u>Component</u>	<u>Inspection Method</u>	<u>Time Required</u>
Intake air filter	Visual	~2 minutes
Injection timing	Photodiode method*	20-30 minutes
	Dial indicator method**	1 hour
EGR system	Application of external vacuum	5-10 minutes (depending on accessibility)
Injectors	Visual check of spray pattern	45 minutes for 4-cylinder engines to 90 minutes for 8-cylinder engines
Anti-tampering seals on injection pumps	Visual check for presence of seal (no a functional check)	~5 minutes

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\*Currently available for GM vehicles; may be available for other models in the near future

\*\*Applicable to Mercedes, VW, Peugeot

- Inspection and setting of injection timing costs between \$25 for GM vehicles (using the newly developed photodiode method) to \$45 for a Bosch VE injection pump. Costs for Mercedes vehicles are higher (\$70).
- Inspection of EGR valve is a very low cost item, but replacement of valve or controls typically costs more than \$50 for Oldsmobile diesels and over a \$100 for Mercedes.
- Removal and inspection of injectors for spray pattern varied from \$30 for VW (4-cylinders) to \$50 for GM (8-cylinders). Mercedes dealers quoted substantially higher costs (\$150-\$200).
- Inspection of anti-tampering seals on the injection pump is a no-cost operation. However, adjustment is typically quite expensive, in excess of \$100.

EEA believes that \$100 cost limit would allow a check and adjustment of air filter, injection timing, EGR and injectors on most diesel vehicles except Mercedes diesels. Replacement of any parts would be over and above the quoted costs, but these parts may be covered under the emissions warranty for vehicles with 50,000 miles or less on the odometer. Replacement of an injector (one) cost \$45-60 (for VW and GM models) for the part costs and 1-hour of labor (\$30-35) for a total cost of \$75-95.

The relationship between smoke opacity and particulate emissions has been the subject of considerable study. One of the main problems in obtaining a relationship is that particulate is measured as the total mass on the FTP, which is a lightly loaded cycle, but high smoke opacity is a "real time" effect that occurs primarily at high loads. Opacity is also typically measured from the "raw" undiluted exhaust plume, whereas particulate is CVS sampled on a "dilute" basis; the correlation between such measurements is difficult. However, researchers have shown correlation between opacity measured on dilute exhaust and particulate. Opacity is affected by the optical qualities of the particulate and has been found to be strongly dependent on the elemental carbon content of the particulate. The weight of particulate emissions depends not only on the elemental carbon but also on the organic fraction; thus the correlation between opacity and particulate will vary by the organic fraction of particulate mass. The only conclusion that we can draw is that all

repairs or adjustments leading to reduced smoke will also reduce particulate and hydrocarbon emissions but the extent of reduction may vary widely.

The ARB has also requested that EEA estimate the effect of the program on decreases in diesel particulate and gaseous emissions. Based on a very small sample of vehicles that were repaired for the components malperformances listed except EGR, we believe that the following values are representative for each repaired light-duty vehicle.

- HC - reduced by 40 to 50 percent
- Particulate - reduced by 15 to 20 percent
- NO<sub>x</sub> - increased by 2 to 5 percent
- CO - essentially unaffected

Repair of vehicles where the EGR system has closed in the "off" position is expected to decrease NO<sub>x</sub> by 30-35 percent with a 5 percent increase in HC and particulate emissions. Note that all the above figures are per repaired vehicle; in order to estimate the fleetwide effect, it is necessary to know the fraction of cars that would fail the inspection program and be repaired. For example, the fleetwide reduction of HC from LDDV's at a 10 percent inspection failure rate would be between 4 and 5 percent ( $0.1 \times 0.4 = 0.04$ ).

#### VALIDATION

As a means to validate the test procedure, EEA tested five cars and one pickup truck equipped with a diesel engine. Since cars to be tested under the validation had to span the range of smoke emissions likely to be encountered, we worked with a local mechanic and used vehicles that came in for repair (after obtaining the owner's permission) for the validation. Moreover, the validation could be conducted only during the period that Wager Co. provided us with the smoke meter; during this period no VW or GM vehicles came in for repairs. However, the tests were conducted as a validation of test method and not of individual make/model

performance. (Later tests using visual observation of tailpipe smoke on VW and GM vehicles subjectively confirmed the trends in smoke opacity observed during the validation testing for the different test modes).

The validation was conducted to ensure that no significant operational difficulties were encountered during the test. Upon ARB's request, we measured smoke opacity at the following modes:

- Idle
- High idle (~2500 RPM)
- WOT 7 second acceleration from rest
- Snap idle
- WOT acceleration from 30-50 mph in top gear

A subjective comment on the smokiness is also provided. Smoke opacity was measured with a Wager P6-P smokemeter loaned to us by the R. H. Wager Co. and mounted as per our recommended procedure (in Table 5-1). Test results are shown in Table 5-3. All the LDV's tested showed a sharp rise in smoke opacity at or very close to engine governed speed. This is noted for those vehicles when this point was reached during the conduct of the particular test cycle. Only two minor operational problems were encountered:

- The clamp for the smoke detector did not fit all the different tailpipe sizes encountered. This was solved by placing a rubber piece between the clamp and exhaust pipe.
- The 30-50 mph acceleration at WOT in top gear was difficult to conduct on vehicles with automatic transmissions, as the transmission would kick down to a lower gear. This was solved by backing off from the throttle slightly to prevent kickdown.

As can be seen from the results, the 7 second acceleration from rest proved to be the most effective test in correlating with a subjective observation of smokiness. EEA does not wish to imply that these six tests represent a complete validation; the tests were conducted to highlight any "in-use" problems that we may not have foreseen theoretically.

TABLE 5-3

RESULTS OF VALIDATION TESTING  
(Smoke Opacity in Percent)

<u>MYR/Make</u>	<u>Odometer (miles)</u>	<u>Idle</u>	<u>Hi-Idle</u>	<u>Snap Idle</u> <sup>1/</sup>	<u>Acceleration in 2nd gear</u>	<u>Acceleration from 30-50 mph</u>	<u>Comment</u>
78 Peugeot 504	51125	6	5	18	20 (40 peak)	20	Little smoke
84 Mercedes 190	11642	2	10	30/60/30	18	40 (80-peak)	High speed smoke <u>not apparent</u>
75 Mercedes 220	88220	2	3	10	7	4	No smoke
76 Peugeot 504	82000	2	~0	40/50/40	50	19	Very smoky
78 Mercedes 240	78003	3	6	35	18	20	Little smoke
82 Mazda Pickup	36278	2	4	8	16	20	Little smoke

<sup>1/</sup>Results of 3 snaps provided if they differ significantly



APPENDIX A

FEDERAL SMOKE TEST PROCEDURE  
FOR HEAVY-DUTY VEHICLES

(f) Equipment, instruments, or tools may not be used to identify malfunctioning, maladjusted, or defective engine components unless the same or equivalent equipment, instruments, or tools will be available to dealerships and other service outlets and

(1) Are used in conjunction with scheduled maintenance on such components,

(2) Are used subsequent to the identification of an engine failure or malfunction, as provided in paragraph (a) (5) (i) of this section for durability engines or paragraph (b) of this section for emission-data engines, or

(3) Unless specifically authorized by the Administrator.

#### § 85.874-7 Service accumulation and emission measurements.

The procedures set forth in this section describe the service accumulation that shall be accomplished on each test engine and when tests are to be conducted.

(a) (1) Emission data engines: Each engine shall be operated with all emission control systems installed and operating on a dynamometer for 125 hours. Exhaust emission tests shall be conducted at zero and 125 hours of operation.

(2) Durability data engines: Each engine shall be operated on a dynamometer for 1,000 hours. Exhaust emission measurements, as prescribed, shall be made at zero-hours and at each 125-hour interval.

(b) A break-in procedure, not to exceed 20 hours, may be run if approved in writing in advance by the Administrator. This procedure would be run after the zero-hour test, and the hours accumulated would not be counted as part of the service accumulation.

(c) Before service accumulation can begin, the following criteria must be met. Failure to comply with these requirements shall invalidate all test data submitted for an engine.

(1) Each engine shall produce at least 95 percent of the maximum rated horsepower, corrected to rating conditions, at 95 to 100 percent of the rated speed.

(2) The fuel rate at maximum horsepower shall be within manufacturer's specifications.

(3) The zero-hour test data shall be provided to the Administrator and the engine shall be made available for such testing under § 85.874-29 as the Administrator may require.

(d) During service accumulation, hours can be credited toward the required service accumulation hours when the following criteria are met. If these criteria cannot be met, engine operation shall be discontinued and the Administrator shall be notified immediately. (Adjustments to the fuel rate can be ap-

proved under the provisions of § 85.874-6.)

(1) Each engine shall produce at least 95 percent of the maximum horsepower, at 95 to 100 percent of the rated speed, observed during zero-hour testing. Horsepower values shall be corrected to the rating conditions.

(2) The engine shall be operated at 75 percent of the inlet and exhaust restrictions specified in § 85.874-12 except that the tolerance shall be  $\pm 3$  inches of water and  $\pm 0.5$  inches of Hg respectively.

(e) During each emission test the inlet and exhaust restrictions shall be as specified in § 85.874-12.

(f) Tests, other than zero-hour tests, may be conducted within eight (8) hours of the nominal test point.

(g) (1) The results of each emission test shall be air posted to the Administrator within 72 hours of test completion (or delivered within five working days). The manufacturer shall furnish to the Administrator an explanation for voiding any test. The Administrator will determine if voiding the test was appropriate based upon the explanation given by the manufacturer for the voided test. If a manufacturer conducts multiple tests (not to exceed three valid tests) at any test point, the number of tests must be the same at each point. The data obtained from all valid tests shall be used in the calculation of the deterioration factor. Tests between test points may be conducted as required by the Administrator. Data from all tests (including voided tests) shall be air posted to the Administrator within 72 hours (or delivered within five working days). In addition, all test data shall be compiled and provided to the Administrator in accordance with § 85.874-4. Where the Administrator conducts a test on a durability engine at a prescribed test point, the results of that test will be used in the calculation of the deterioration factor.

(2) The results of all emission tests shall be recorded and reported to the Administrator using two places to the right of the decimal point. These numbers shall be rounded in accordance with the "Rounding Off Method" specified in ASTM E 29-67.

(h) Once a manufacturer begins to operate an emission data or durability data engine, as indicated by compliance with paragraph (c) of this section, he shall continue to run the engine to 125 hours or 1,000 hours, respectively, and the data from the engine shall be used in the calculations under § 85.874-19. Discontinuation of an engine shall be allowed only with the prior written consent of the Administrator.

(i) (1) The Administrator may elect to operate and test any test engine during all or any part of the service accumula-

tion and testing procedure. In such cases, the manufacturer shall provide the engine(s) to the Administrator with all information necessary to conduct the testing.

(2) The test procedures (§ 85.874-9 through § 85.874-18) will be followed by the Administrator. The Administrator will test the engines at each test point. Maintenance may be performed by the manufacturer under such conditions as the Administrator may prescribe.

(3) The data developed by the Administrator for the engine-system combination shall be combined with any applicable data supplied by the manufacturer on other engines of that combination to determine the applicable deterioration factors for the combination. In the case of a significant discrepancy between data developed by the Administrator and that submitted by the manufacturer, the Administrator's data shall be used in the determination of deterioration factors.

(j) Emission testing of any type with respect to any certification engine other than that specified in this subpart is not allowed except as such testing may be specifically authorized by the Administrator.

#### § 85.874-8 Special test procedures.

(a) The Administrator may prescribe test procedures, other than those set forth in this subpart, for any motor vehicle engine which he determines is not susceptible to satisfactory testing by the procedures set forth herein.

#### § 85.874-9 Test procedures.

The procedures described in this and subsequent sections will be the test program to determine the conformity of engines with the standard set forth in § 85.874-1.

(a) The test consists of a prescribed sequence of engine operating conditions on an engine dynamometer with continuous examination of the exhaust gases. The test is applicable equally to controlled engines equipped with means for preventing, controlling, or eliminating smoke emissions and to uncontrolled engines.

(b) The test is designed to determine the opacity of smoke in exhaust emissions during those engine operating conditions which tend to promote smoke from diesel-powered vehicles.

(c) The test procedure begins with a warm engine which is then run through preloading and preconditioning operation. After an idling period, the engine is operated through acceleration and lugging modes during which smoke emission measurements are made to compare with the standards. The engine is then

returned to the idle condition and the acceleration and lugging modes are repeated. Three sequences of acceleration and lugging constitute the full set of operating conditions for smoke emission measurement.

(d) Except in cases of component malfunction or failure, all emission control systems installed on or incorporated in a new motor vehicle engine shall be functioning during all procedures in this subpart. Maintenance to correct component malfunction or failure shall be authorized in accordance with § 85.874-6.

**§ 85.874-10 Diesel fuel specifications.**

(a) The diesel fuels employed shall be clean and bright, with pour and cloud points adequate for operability. The fuels may contain nonmetallic additives as follows: cetane improver, metal deactivator, antioxidant, dehazer, antirust, pour depressant, dye, and dispersant.

(b) Fuel meeting the following specifications, or substantially equivalent specifications approved by the Administrator, shall be used in exhaust emission testing. The grade of fuel recommended by the engine manufacturer, commercially designated as "Type 1-D" or "Type 2-D," shall be used.

required in paragraph (a) (2) (ii) of this section, but before the speed exceeds 90 percent of the rated speed, the throttle shall be moved rapidly to, and held in, the fully-closed position. Immediately after the throttle is closed, the preselected load required to perform the acceleration in paragraph (a) (2) (iv) of this section shall be applied.

(iv) When the engine decelerates to the maximum torque speed or 60 percent of rated speed (within 50 r.p.m.), whichever is higher, the throttle shall be moved rapidly to, and held in, the fully-open position. The preselected dynamometer load which was applied during the preceding transition period shall be used to control the acceleration of the engine so that the speed increases to at least 95 percent of the rated speed in  $10 \pm 2$  seconds.

(3) *Lugging mode.* (i) Immediately upon completion of the preceding acceleration mode, the dynamometer controls shall be adjusted to permit the engine to develop maximum horsepower at rated speed. This transition period shall be 50 to 60 seconds in duration. During the last ten seconds of this period, the engine speed shall be maintained within 50 r.p.m. of the rated speed, and the power (corrected, if necessary, to rating conditions) shall be no less than 95 percent of the maximum horsepower developed during zero-hour testing.

(ii) With the throttle remaining in the fully-open position, the dynamometer controls shall be adjusted gradually so that the engine speed is reduced to the maximum torque speed or to 60 percent of the rated speed (within 50 r.p.m.), whichever is higher. This lugging operation shall be performed smoothly over a period of  $35 \pm 5$  seconds. The rate of slowing of the engine shall be linear, within 100 r.p.m. as specified in § 85.874-17(c).

(4) *Engine unloading.* Immediately upon completion of the preceding lugging mode, the dynamometer and engine shall be returned to the idle condition described in paragraph (a) (1) of this section.

(b) The procedures described in paragraphs (a) (1) through (a) (4) of this section shall be repeated until three consecutive valid cycles have been completed. If three valid cycles have not been completed after a total of six consecutive cycles have been run, the engine shall be preconditioned by operation at maximum horsepower at rated speed for 10 minutes before the test sequence is repeated.

**§ 85.874-12 Dynamometer and engine equipment.**

The following equipment shall be used for smoke emission testing of engines on engine dynamometers.

Item	ASTM test method No.	Type 1-D	Type 2-D
Cetane.....	D 613		
Distillation range.....	D 86	48-54	42-50
IBP, ° F.....			
10 percent point, ° F.....		330-360	340-400
50 percent point, ° F.....		370-430	400-460
90 percent point, ° F.....		410-480	470-540
EP, ° F.....		490-520	550-610
Gravity, ° API.....	D 287	500-560	580-660
Total sulfur, percent.....	D 129 or D 2022	40-44	33-37
Hydrocarbon composition.....	D 1139	0.05-0.20	0.2-0.5
Aromatics, percent.....			
Paraffins, Naphthenes, Olefins.....		8-15	27 (Min.)
Flash point, ° F (Min.).....	D 93	Remainder	Remainder
Viscosity, centistokes.....	D 445	120	130
		1.6-2.0	2.0-3.2

(c) Fuel meeting the following specifications, or substantially equivalent specifications approved by the Administrator, shall be used in service accumulation. The grade of fuel recommended by the engine manufacturer, commercially designated as "Type 1-D" or "Type 2-D," shall be used.

Item	ASTM test method No.	Type 1-D	Type 2-D
Cetane.....	D 613		
Distillation range.....	D 86	48-54	42-55
IBP, ° F.....			
10 percent point, ° F.....		320-350	340-410
50 percent point, ° F.....		370-430	400-470
90 percent point, ° F.....		410-480	470-540
EP, ° F.....		460-520	550-610
Gravity, ° API.....	D 287	500-560	580-660
Total sulfur, percent.....	D 129 or D 2022	40-44	33-40
Flash point, ° F (Min.).....	D 93	0.05-0.20	0.2-0.5
Viscosity, centistokes.....	D 445	120	130
		1.6-2.0	2.0-3.2

(d) The type fuel, including additive and other specifications, used under paragraphs (b) and (c) of this section shall be reported in accordance with § 85.874-2(b) (3).

**§ 85.874-11 Dynamometer operation cycle for smoke emission tests.**

(a) The following sequence of operations shall be performed during engine dynamometer testing of smoke emissions, starting with the dynamometer preloading determined and the engine preconditioned (§ 85.874-16(c)).

(1) *Idle mode.* The engine is caused to idle for 5 to 5.5 minutes at the manufacturer's recommended low idle speed. The dynamometer controls shall be set to provide minimum load by turning the load switch to the "off" position or by

adjusting the controls to the minimum load position.

(2) *Acceleration mode.* (i) The engine speed shall be increased to  $200 \pm 50$  r.p.m. above the manufacturer's recommended low idle speed within 3 seconds.

(ii) Immediately upon completion of the mode specified in paragraph (a) (2) (i) of this section, the throttle shall be moved rapidly to, and held in, the fully-open position. The inertia of the engine and the dynamometer, or alternately a preselected dynamometer load, shall be used to control the acceleration of the engine so that the speed increases to 85 percent of the rated speed in  $5 \pm 1.5$  seconds. This acceleration shall be linear within 100 r.p.m. as specified in § 85.874-17(c).

(iii) After the engine reaches the speed

(a) An engine dynamometer with adequate characteristics to perform the test cycle described in § 85.874-10.

(b) An engine cooling system having sufficient capacity to maintain the engine at normal operating temperatures during conduct of the prescribed engine tests.

(c) A noninsulated exhaust system extending  $15 \pm 5$  feet from the exhaust manifold, or the crossover junction in the case of Vee engines, and presenting an exhaust back pressure within  $\pm 0.2$  inch Hg. of the upper limit at maximum rated horsepower, as established by the engine manufacturer in his sales and service literature for vehicle application. A conventional automotive muffler of a size and type commonly used with the engine being tested shall be employed in the exhaust system during smoke emission testing. The terminal 2 feet of the exhaust pipe shall be circular cross section and be free of elbows and bends. The end of the pipe shall be cut off

squarely. The terminal 2 feet of the exhaust pipe shall have a diameter in accordance with the engine being tested, as specified below:

Maximum rated horsepower:	Exhaust pipe diameter (inches)
Less than 101.....	2
101-200.....	3
201-300.....	4
301 or more.....	5

(d) An engine air inlet system presenting an air inlet restriction within  $\pm 1$  inch of water of the upper limit for the engine operating condition which results in maximum air flow, as established by the engine manufacturer in his sales and service literature, for the engine being tested.

#### § 85.874-13 Smoke measurement system.

(a) *Schematic drawing.* The following figure (fig. I874-1) is a schematic drawing of the optical system of the light extinction meter.

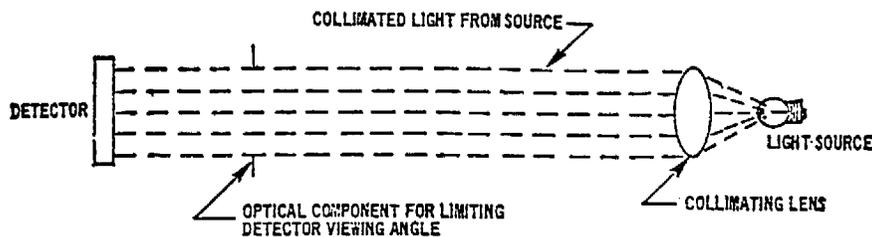


FIGURE I874-1.—EPA smokemeter optical system (schematic).

(b) *Equipment.* The following equipment shall be used in the system:

(1) *Adapter*—the smokemeter optical unit may be mounted on a fixed or movable frame. The normal unrestricted shape of the exhaust plume shall not be modified by the adapter, the meter, or any ventilation system used to remove the exhaust from the test site.

(2) *Smokemeter (light extinction meter)*—continuous recording, full-flow light obscuration meter. It shall be positioned near the end of the exhaust pipe so that a built-in light beam traverses the exhaust smoke plume which issues from the pipe at right angles to the axis of the plume. The light source is an incandescent lamp operated at a constant voltage of not less than 15 percent of the manufacturer's specified voltage. The lamp output is collimated to a beam with a nominal diameter of 1.125 inches. The angle of divergence of the collimated beam shall be within  $4^\circ$  included angle. A light detector, directly opposed to the light source, measures the amount of light blocked by the smoke in the exhaust. The detector sensitivity is restricted to the visual range and comparable to that of the human eye. A col-

limiting tube with apertures equal to the beam diameter is attached to the detector. It restricts the viewing angle of the detector to within  $16^\circ$  included angle. An amplified signal corresponding to the amount of light blocked is recorded continuously on a remote recorder. An air curtain across the light source and detector window assemblies may be used to minimize deposition of smoke particles on those surfaces provided that it does not measurably affect the opacity of the plume. The meter consists of two units, an optical unit and a remote control unit. Light extinction meters employing substantially identical measurement principles and producing substantially equivalent results but which employ other electronic and optical techniques may be used only after having been approved in advance by the Administrator.

(3) *Recorder*—a continuous recorder, with variable chart speed over a minimal range of 0.5 to 8.0 inches per minute (or equivalent) and an automatic marker indicating 1-second intervals shall be used for continuously recording the exhaust gas opacity, engine r.p.m. and throttle position. The recorder shall

be equipped to indicate only when the throttle is in the fully-open or fully-closed position. The recorder scale for opacity shall be linear and calibrated to read from 0 to 100 percent opacity full scale. The opacity trace shall have a resolution within 1 percent opacity. The recorder scale for engine r.p.m. shall be linear and have a resolution of 30 r.p.m. The throttle position trace must clearly indicate when the throttle is in the fully-open and fully-closed positions. Any means other than a strip-chart recorder may be used provided it produces a permanent visual data record of quality equal to or better than that described above.

(4) The recorder used with the smoke-meter shall be capable of full-scale deflection in 0.5 second or less. The smoke-meter-recorder combination may be damped so that signals with a frequency higher than 10 cycles per second are attenuated. A separate low-pass electronic filter with the following performance characteristics may be installed between the smokemeter and the recorder to achieve the high-frequency attenuation.

(i) 3 decibel point—10 cycles per second.

(ii) Insertion loss—zero  $\pm 0.5$  decibels.

(iii) Selectivity—12 decibels per octave above 10 cycles per second.

(iv) Attenuation—27 decibels down at 40 cycles per second minimum.

(c) *Assembling equipment.* (1) The optical unit of the smokemeter shall be mounted radially to the exhaust pipe so that the measurement will be made at right angles to the axis of the exhaust plume. The distance from the optical centerline to the exhaust pipe outlet shall be  $5 \pm 1$  inch. The full flow of the exhaust stream shall be centered between the source and detector apertures (or windows and lenses) and on the axis of the light beam.

(2) Power shall be supplied to the control unit of the smokemeter in time to allow at least 15 minutes for stabilization prior to testing.

#### § 85.874-14 Information to be recorded.

The following information shall be recorded with respect to each test:

(a) Test number.

(b) Date and time of day.

(c) Instrument operator.

(d) Engine operator.

(e) Engine Identification numbers—

Date of manufacture—Number of hours of operation accumulated on engine—Engine family—Exhaust pipe diameter—Fuel injector type—Maximum measured fuel rate at maximum measured torque and horsepower—Air aspiration system—Low idle r.p.m.—Maximum governed r.p.m.—Maximum meas-

ured horsepower at r.p.m.—Maximum measured torque at r.p.m.—Exhaust system back pressure—Air inlet restriction.

(f) Smokemeter: Number—Zero control setting—Calibration control setting—Gain.

(g) Recorder chart: Identify zero traces—calibration traces—Idle traces—Closed throttle trace, open throttle trace—Acceleration and lug down test traces—Start and finish of each test.

(h) Ambient temperature in dynamometer testing room.

(i) Engine intake air temperature and humidity.

(j) Barometric pressure.

(k) Observed engine torque and speed during the steady-state test conditions specified in § 85.874-11(a) (3) (i).

#### § 85.874-15 Instrument checks.

(a) The smokemeter shall be checked according to the following procedure prior to each test:

(1) The optical surfaces of the optical section shall be checked to verify that they are clean and free of foreign material and fingerprints.

(2) The zero control shall be adjusted under conditions of "no smoke" to give a recorder trace of zero.

(3) Calibrated neutral density filters having approximately 10, 20, and 40 percent opacity shall be employed to check the linearity of the instrument. The filter(s) shall be inserted in the light path perpendicular to the axis of the beam and adjacent to the opening from which the beam of light from the light source emanates, and the recorder response shall be noted. The nominal opacity value of the filter will be confirmed by the Administrator. Deviations in excess of 1 percent of the nominal opacity shall be corrected.

(b) The instruments for measuring and recording engine r.p.m., engine torque, air inlet restrictions, exhaust system back pressure, throttle position, etc., which are used in the tests prescribed herein, shall be calibrated in accordance with good engineering practice. Opacity filters shall be calibrated semi-annually.

#### § 85.874-16 Test run.

(a) The temperature of the air supplied to the engine shall be between 68° F. and 86° F. The observed barometric pressure shall be between 28.5 inches and 31 inches Hg. Higher air temperature or lower barometric pressure may be used, if desired, but no allowance will be made for possible increased smoke emissions because of such conditions.

(b) The governor and fuel system shall have been adjusted to provide en-

gine performance at the levels specified by the engine manufacturer for maximum rated horsepower and maximum rated torque. These specifications shall be reported in accordance with § 85.874-2 (b) (3).

(c) The following steps shall be taken for each test:

(1) Start cooling system.

(2) Starting with a warmed engine, determine by experimentation the dynamometer inertia and dynamometer load required to perform the acceleration in the dynamometer cycle for smoke emission tests (§ 85.874-11(a) (2)). In a manner appropriate for the dynamometer and controls being used, arrange to conduct the acceleration mode.

(3) Install smokemeter optical unit and connect it to the recorder. Connect the engine r.p.m. and torque sensing devices to the recorder.

(4) Turn on purge air to the optical unit of the smokemeter, if purge air is used.

(5) Check and record zero and span settings of the smokemeter recorder at a chart speed of approximately 1 inch per minute. (The optical unit shall be retracted from its position about the exhaust stream if the engine is left running.)

(6) Precondition the engine by operating it for 10 minutes at maximum rated horsepower.

(7) Proceed with the sequence of smoke emission measurements on the engine dynamometer as prescribed in § 85.874-11.

(8) During the test sequence of § 85.874-11, continuously record smoke measurements, engine r.p.m., and throttle position at a minimum chart speed of 1 inch per minute during the idle mode and transitional periods and 8 inches per minute during the acceleration and lugging modes. The smokemeter zero and full scale recorder deflections may be rechecked during the idle mode of each test sequence. If either zero or full scale drift is in excess of 2 percent opacity, the smokemeter controls must be readjusted and the test must be repeated.

(9) Turn off engine.

(10) Check zero and reset if necessary and check span of the smokemeter recorder by inserting neutral density filters. If either zero or span drift is in excess of 2 percent opacity, the test results shall be invalidated.

#### § 85.874-17 Chart reading.

The following procedure shall be used to analyze the recorder chart.

(a) Locate the modes specified in § 85.874-11(a) (1) through (a) (4) by ap-

plying the following starting and ending criteria.

(1) The idle mode specified in § 85.874-11(a) (1) starts when engine preconditioning or the lugging mode of a preceding cycle has been completed and ends when the engine speed is raised above the idle speed.

(2) The acceleration mode specified in § 85.874-11(a) (2) (i) starts when the preceding idle mode has been completed and ends when the throttle is in the fully open position as indicated by the throttle position trace.

(3) The acceleration mode specified in § 85.874-11(a) (2) (ii) starts when the preceding acceleration mode has been completed and ends when the engine speed reaches 85 percent of the rated speed.

(4) The transition period specified in § 85.874-11(a) (2) (iii) starts when the throttle is in the fully closed position and ends when the throttle is in the fully open position as indicated by the throttle position trace.

(5) The acceleration mode specified in § 85.874-11(a) (2) (iv) starts when the preceding transition period has been completed and ends when the engine speed reaches 95 percent of the rated speed.

(6) The transition period specified in § 85.874-11(a) (3) (i) starts when the preceding acceleration mode has been completed and ends when the engine speed is 50 r.p.m. below the rated speed and the provisions of § 85.874-11(a) (3) (i) are met.

(7) The lugging mode specified in § 85.874-11(a) (3) (ii) starts when the preceding transition period has been completed and ends when the engine speed is at the maximum torque speed or at 60 percent of the rated speed, whichever is higher.

(b) Determine if the test requirements of § 85.874-11 are met by applying the following modal criteria.

(1) Idle mode as specified in § 85.874-11(a) (1):

(i) Duration: 5 to 5.5 minutes.

(ii) Speed: within specifications.

(2) Acceleration mode as specified in § 85.874-11(a) (2) (i):

(i) Duration: 3 seconds or less.

(ii) Speed increase:  $200 \pm 50$  r.p.m.

(iii) Throttle position: fully open until speed is at least 85 percent of the rated speed.

(3) Acceleration mode as specified in § 85.874-11(a) (2) (ii):

(i) Linearity:  $\pm 100$  r.p.m. as specified in paragraph (c) of this section.

(ii) Duration: 3.5 to 6.5 seconds.

(iii) Throttle position: fully open speed is at least 85 percent of the rated speed.

(4) Transition period as specified in § 85.874-11(a)(2)(iii):

(i) Throttle position: fully closed before speed exceeds 90 percent of the rated speed.

(5) Acceleration mode as specified in § 85.874-11(a)(2)(iv):

(i) Duration: 8 to 12 seconds.

(ii) Throttle position: fully open when speed is at maximum torque speed or at 60 percent of rated speed (within 50 r.p.m.) whichever is higher.

(6) Transition period as specified in § 85.874-11(a)(3)(i):

(i) Duration: 50 to 60 seconds.

(ii) Speed during last 10 seconds: within  $\pm 50$  r.p.m. of rated speed.

(iii) Corrected power during last 10 seconds: at least 95 percent of horsepower developed during zero-hour testing.

(7) Lugging mode as specified in § 85.874-11(a)(3)(ii):

(i) Linearity:  $\pm 100$  r.p.m. as specified in paragraph (c) of this section.

(ii) Duration: 30 to 40 seconds.

(iii) Speed at end: maximum torque speed or 60 percent of rated speed, whichever is higher.

(c) Determine if the linearity requirements of § 85.874-11 were met by means of the following procedure.

(1) For the acceleration mode specified in § 85.874-11(a)(2)(ii), note the maximum deflection of the r.p.m. trace from a straight line drawn between the starting and ending points specified in paragraph (a)(3) of this section.

(2) For the lugging mode specified in § 85.874-11(a)(3)(ii), note the maximum deflection of the r.p.m. trace from a straight line drawn from the starting and ending points specified in paragraph (a)(7) of this section.

(3) The test results will be invalid if any deflection is greater than 100 r.p.m.

(d) Analyze the smoke trace by means of the following procedure.

(1) Starting at the beginning of the first acceleration, as defined in paragraph (a)(2) of this section and stopping at the end of the second acceleration, as defined in paragraph (a)(3) of this section, divide the smoke trace into  $\frac{1}{2}$ -second intervals. Similarly, divide into  $\frac{1}{2}$ -second intervals the third acceleration mode and the lugging mode as defined by paragraphs (a)(5) and (7) of this section, respectively.

(2) Determine the average smoke reading during each  $\frac{1}{2}$ -second interval.

(3) Locate and record the 15 highest  $\frac{1}{2}$ -second readings during the acceleration mode of each dynamometer cycle.

(4) Locate and record the five highest  $\frac{1}{2}$ -second readings during the lugging mode of each dynamometer cycle.

(5) Examine the average  $\frac{1}{2}$ -second values which were determined in para-

graphs (d)(3) and (4) of this section and record the three highest values for each dynamometer cycle.

#### § 85.874-18 Calculations.

(a) Average the 45 readings in § 85.874-17(d)(3) and designate the value as "a".

(b) Average the 15 readings in § 85.874-17(d)(4) and designate the value as "b".

(c) Average the nine readings in § 85.874-17(d)(5) and designate the value as "c".

#### §§ 85.874-19—85.874-27 [Reserved]

#### § 85.874-28 Compliance with emission standards.

(a) The emission standards in § 85.874-1 and § 85.974-1 apply to the emissions of engines for their useful lives.

(b) Since emission control efficiency decreases with the accumulation of hours on the engine, the emission level of an engine which has accumulated 1,000 hours of dynamometer operation will be used as the basis for determining compliance with the standards.

(c) The procedure for determining compliance with emission standards in heavy duty diesel engines is as follows:

(1) Emission deterioration factors for the acceleration mode (designated as "A"), the lugging mode (designated as "B"), the peak opacity (designated as "C"), the CO exhaust emissions, and the HC+NOx exhaust emissions shall be established separately for each engine-system combination.

(i) The applicable results to be used in determining the deterioration factors for each combination shall be:

(A) All emission data from the tests required under § 85.874-7(a)(2), except the zero-hour tests. This shall include the official test results, as determined in § 85.874-29, for all tests conducted on all durability engines of the combination selected under § 85.874-5(c) (including all engines selected to be operated by the manufacturer under § 85.874-5(c)(2)).

(B) All emission data from the tests conducted before and after the maintenance provided in § 85.874-6(a)(1)(i) if emission tests were conducted.

(C) All emission data from the tests conducted before and after maintenance provided in § 85.874-6(a)(5)(iii) if emission tests were conducted.

(ii) All applicable emission results for (A) HC+NOx, (B) CO, (C) acceleration smoke ("a"), (D) lugging smoke ("b"), and (E) peak smoke ("c") shall be plotted as a function of durability hours which shall be consistently rounded to the nearest hour. Emission data shall have two figures to the right of the decimal. The best fit straight lines, fitted by

the method of least squares, shall be drawn through these data points. The interpolated 125- and 1000-hour points on each line, rounded to whole numbers in accordance with ASTM E29-87, must be within the standards specified in § 85.874-1 for smoke emissions and § 85.974-1 for gaseous emissions or the data shall not be used in the calculation of a deterioration factor, unless no applicable data points exceeded the standards.

(iii) The interpolated values shall be used to calculate a deterioration factor as follows:

Factor—Exhaust emissions (both smoke and gaseous) interpolated to 1000 hours minus the exhaust emissions interpolated to 125 hours. (Negative deterioration factors shall be considered zero).

(2) The appropriate deterioration factor, carried out to two places to the right of the decimal point, shall be added to the exhaust emission test results, carried out to two places to the right of the decimal point, for each emission data engine.

(3) The emission values to compare with the standards shall be the adjusted emission values of paragraph (c)(2) of this section rounded to whole numbers in accordance with ASTM E 29-87 for each emission data engine.

(4) Every test engine of an engine family must comply with all applicable standards, as determined in paragraph (c)(3) of this section, before any engine in that family will be certified.

#### § 85.874-29 Testing by the Administrator.

(a) The Administrator may require that any one or more of the test engines be submitted to him, at such place or places as he may designate, for the purpose of conducting emissions tests. The Administrator may specify that he will conduct such testing at the manufacturer's facility, in which case instrumentation and equipment specified by the Administrator shall be made available by the manufacturer for test operations. Any testing conducted at a manufacturer's facility pursuant to this paragraph shall be scheduled by the manufacturer as promptly as possible.

(b)(1) Whenever the Administrator conducts a test on a test engine the results of that test, unless subsequently invalidated by the Administrator, shall comprise the official data for the engine at that prescribed test point and the manufacturer's data for that prescribed test point shall not be used in determining compliance with emission standards.

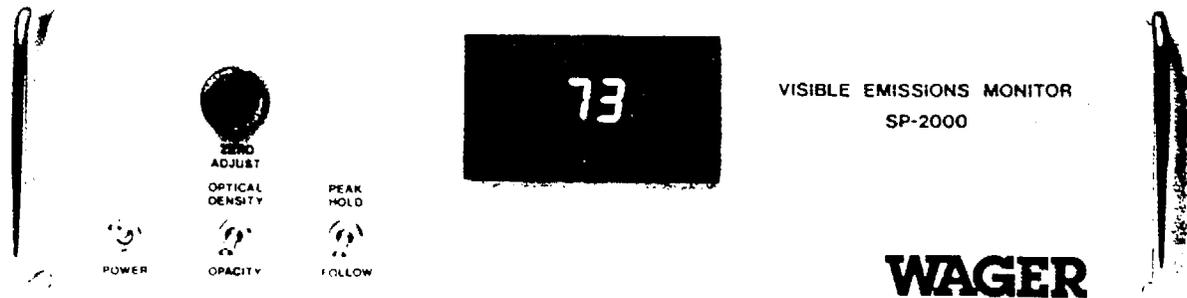
(2) Whenever the Administrator does not conduct a test on a test engine at a test point, the manufacturer's test data will be accepted as the official data for that test point: *Provided*, That if the

APPENDIX B

SMOKEMETER SPECIFICATIONS

# Look At Us NOW!

---



## Our NEW SP-2000 Series Visible Emissions Monitor

- Digital display
- Readings of both Optical Density and Opacity
- Just 4 controls
- Rugged as ever
- Accurate as ever—to within 1%, even in ambient light

Our new and traditional Wager features give you incomparable performance in Visible Emissions Monitoring. Let us send you product details.

Wager SP-2000 monitors, backed by 1-year warranty, comply with EPA spectral specifications, and all existing ISO and SAE specifications.

---

Write us or call:

# WAGER

Robert H. Wager Co., Inc.  
Passaic Avenue  
Chatham, NJ 07928  
(201) 635-9200



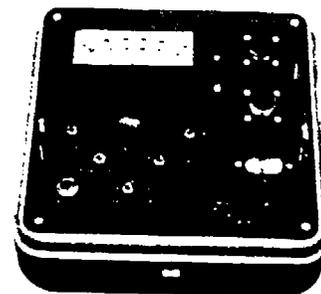
# Wager Portable Smoke Exhaust Monitor (Model P-6P)

For Diesel Fleet  
Maintenance,  
Compliance With Air  
Quality Standards.



# WAGER

# Wager Portable Smoke Exhaust Monitor (Model P-6P)



This handy portable smoke monitor makes it easy to get an accurate reading of diesel exhaust emissions, both on the road and in maintenance facilities of truck and bus fleets. Its use promotes combustion efficiency for fuel economy, and insures compliance with diesel emission standards set by environmental air quality codes.

The Wager P-6P provides a smoke reading which can be advantageously used as a diagnostic reference for tuning, overhaul, and general maintenance of car, tractor, and small stationary diesel engines. Its application extends to automotive rebuilding centers, test centers, service areas, engine manufacturers and distributors.

## Design/Operation

The Wager Model P-6P consists of a portable stack monitor that is cable connected to a portable control unit with meter.

The stack monitor clamps to exhaust stacks of any configuration, all diameters up to 6 inches. A light sensor in this monitor reads the opacity of emissions to 1% accuracy full scale and relays its precise readings to the control unit. Here, a meter displays the exhaust opacity read-outs on two scales, 0-100% and 0-20%.

**The Stack Monitor:** This monitor employs a single pass system and has an operating distance of 7". A pulsed LED emitter as the monitor's light source insures the 1% accuracy of readings even in direct sun or artificial ambient light.

**The Cable:** This connecting cable is of 25-foot length, allowing complete mobility in service or test bay areas, or convenient placement in the truck cab on fleet vehicle runs.

**The Control Unit:** For portability and protection, the control unit is housed in a lightweight, weatherproof, fiberglass case. The large dial meter permits easy reading, and the meter comes with a "peak hold" feature that shows the largest opacity reading. The control unit also has analog output for chart recorder or computer.

**Power:** The Wager P-6P can be powered by a rechargeable battery or line power. The battery supplied with the Wager P-6P gives 8-10 hours of service before requiring recharging, and has a fast or slow charging rate, with automatic shut-off once the battery is completely charged.

## Features

### Accurate

- All read-outs are within 1% on a scale of 0-100%.
- Unit has been temperature compensated.
- Initially calibrated under clear stack conditions, checking unit at 0% and 100% opacity.
- Meter can be further checked for accuracy with a hand inserted neutral density filter.

### Reliable

- Minimum drift, zero stability less than 1% in ten hours.
- Pulsed LED has indefinite life expectancy.
- Exceptionally good linearity & resolution.
- Complies with EPA spectral specifications.
- Meets existing and proposed ISO and SAE specifications.
- Comes with 1-year warranty.

### Low Maintenance

- All solid state electronics, mil spec throughout.
- Battery is a sealed maintenance free type.
- Easy lens accessibility.
- Baffle plates on interior faces of monitor help maintain lens cleanliness.

### Rugged

- Portable control panel is in a lightweight, weatherproof, fiberglass case.
- Monitoring head clamps securely onto tailpipe.

### Versatile and Compatible

- Mobile measuring capabilities with battery control and long 25' cable.
- Battery provides 8-10 hours of service before requiring recharging.
- Can operate on AC power with battery charging at same time.
- Seven inch monitoring head clamps onto any tailpipe configuration.
- Works in conjunction with chassis dynamometers for engine emissions diagnosis and adjustment.

For additional details:

# WAGER

Robert H. Wager Co., Inc.  
Passaic Avenue  
Chatham, NJ 07928 USA  
Tel: (201) 635-9200

# TEST & MAINTENANCE PROGRESS

## New Jersey Updates Diesel Bus Smoke Test Equipment

The New Jersey Department of Environmental Protection (DEP) has replaced its first generation diesel bus smoke meters with 35 new units. New Jersey Department of Transportation (DOT) investigators will soon be using this equipment to perform exhaust tests on New Jersey's 5000 diesel public transportation buses twice each year. Operators of vehicles found to exceed established standards are given the opportunity at the time of the test to perform minor maintenance so that the vehicle complies with standards. If, after this simple maintenance, the bus still cannot comply with the standards, DOT removes it from service until the necessary corrective maintenance has been completed.

New Jersey has been recognized as a leader in its air pollution control programs. Its efforts to control hydrocarbon and carbon monoxide emissions

from automobiles resulted in New Jersey's implementing the first statewide mandatory automobile emissions testing program. Although this automotive program was implemented in 1974, and is the oldest in the nation, the diesel bus testing program dates back to June 18, 1971. As the Reagan administration proceeds with its plans to delegate more enforcement activities to state agencies, it is quite possible that the updated diesel bus testing program could, once again, move New Jersey to the forefront of emission testing.

"New Jersey is proud of its progress made toward cleaner air," said DEP Commissioner Jerry Fitzgerald English. "Through the support of the New Jersey legislature and the motoring public, we have successfully implemented effective control programs which have led to improved ambient air quality."

The progress made by New Jersey didn't happen overnight. The original New Jersey Air Pollution Control Act is dated 1954. The DEP was created in



Light and receiving units are attached to a portable yoke which clamps to the exhaust stack. Below the stack monitor is the control unit. It connects to the monitor with a 25 ft. cable.

1970, and on June 18, 1971, New Jersey Administrative Code, Title 7, Chapter 27, Subchapter 14, entitled "Control and Prohibition of Air Pollution From Diesel Powered Motor Vehicles," was adopted. This regulation established inspection standards for smoke from diesel powered heavy-duty vehicles. Extensive use of the original testing equipment during the past ten years has resulted in deterioration of the smoke meters.

"It became apparent that if the State of New Jersey was to continue its diesel bus smoke testing program, new test equipment needed to be purchased," said George Tyler, DEP's assistant commissioner for environmental management and control. "To check smoke emissions on a routine basis requires a simple monitoring device. Since this device would be used by DOT investigators traveling throughout the state, it was necessary that it be portable."

The equipment that met all of New Jersey's needs for a portable smoke opacity meter was developed and manufactured by the Robert H. Wager Co., Inc., Chatham, N.J. Wager Co. was recently awarded a contract by DEP to supply the needed 35 units for the DOT statewide enforcement program.

"Basically, the New Jersey unit is our standard portable smoke opacity monitor," says Michael Wager, president of the New Jersey company. "These portables have gained rapid acceptance for diesel engine maintenance. But, for



Wager Company personnel instructing Transport of New Jersey employees in the use of the Wager P-6P Control unit. The units are portable, a feature that is important in conducting on-site fleet tests.

New Jersey's particular inspection needs, we did develop some special features they requested.

"For example, our stack monitor normally clamps by hand clamp to the exhaust stack. DOT will continue to use these hand clamps for mobile testing of vehicles, to check emissions while a vehicle is moving under load conditions. But for quick stationary testing, investigators may simply hold the monitor up to the stack, in place, with a magnetic device we designed.

"For additional convenience to their investigators, we also incorporated a 'peak hold' set point into our opacity meter, which shows peak opacity level until reset," Wager said.

The Wager monitors are portable, suit all mobile and stationary testing needs, and measure the opacity of diesel emissions to 1% accuracy under all testing conditions of weather and light.

A light sensor in the stack monitor reads emissions to this 1% accuracy and is cable-connected to relay its readings to a portable meter housed in a lightweight, waterproof fiberglass case. The connecting cable is 25 ft. in length, allowing mobility in testing. With cable, the complete Wager unit is easily transported about on the back seat or in the trunk of the investigator's car.

The accuracy of the electronic, photoelectric Wager monitor is insured by

the use of a pulsed green gallium phosphide LED emitter as the light source, so no interference to readings is encountered from ambient light. Opacity readings, to 1% accuracy even in direct sun, are displayed on the portable meter on two scales: 0 to 100% and 0-20%. The control, in addition to the 'peak hold' feature, has a recorder output for a remote meter or strip recorder.

The system operates from an internal, rechargeable 12 volt, gelatin battery, which can be charged at any time by plugging the line cord into a 115 V a.c. outlet and setting the unit on a slow or fast charging rate. The battery provides at least eight hours of continuous operation before requiring recharging.

Tyler emphasizes, "Award to the Robert H. Wager Co., Inc. of contract for these units was entirely on a bid basis, with demonstration and test performance mandatory."

Allen Johnson, DEP's coordinator said, "We like the portability of the units, which was required to allow DOT flexibility in conducting on-site tests at fleet terminals." Johnson added, "These monitors are simple to use. Five minutes of instruction, and the investigators are on their way."

Michael Wager is certain his company's monitors will measure up to New Jersey's expectations. "Our experience in smoke monitoring goes back into the 1930s, in the marine field, in monitoring smoke emissions for optimum boiler efficiency aboard ships.

"Today's growing concern for the environment has prompted considerable and continuous R&D on our part, with our development of a range of smoke monitors for industry, for routine and special situations of all sorts.

"Diesel emissions monitoring has been a part of this — retractable stack monitors for engine test bays, for example, as well as our portables.

"We are pleased to have been called on to assist in the New Jersey program, and to have worked with state officials to provide the diesel emission monitors they required," Wager said. Continued enforcement of a strict diesel emissions code now seems to be assured for New Jersey. ★



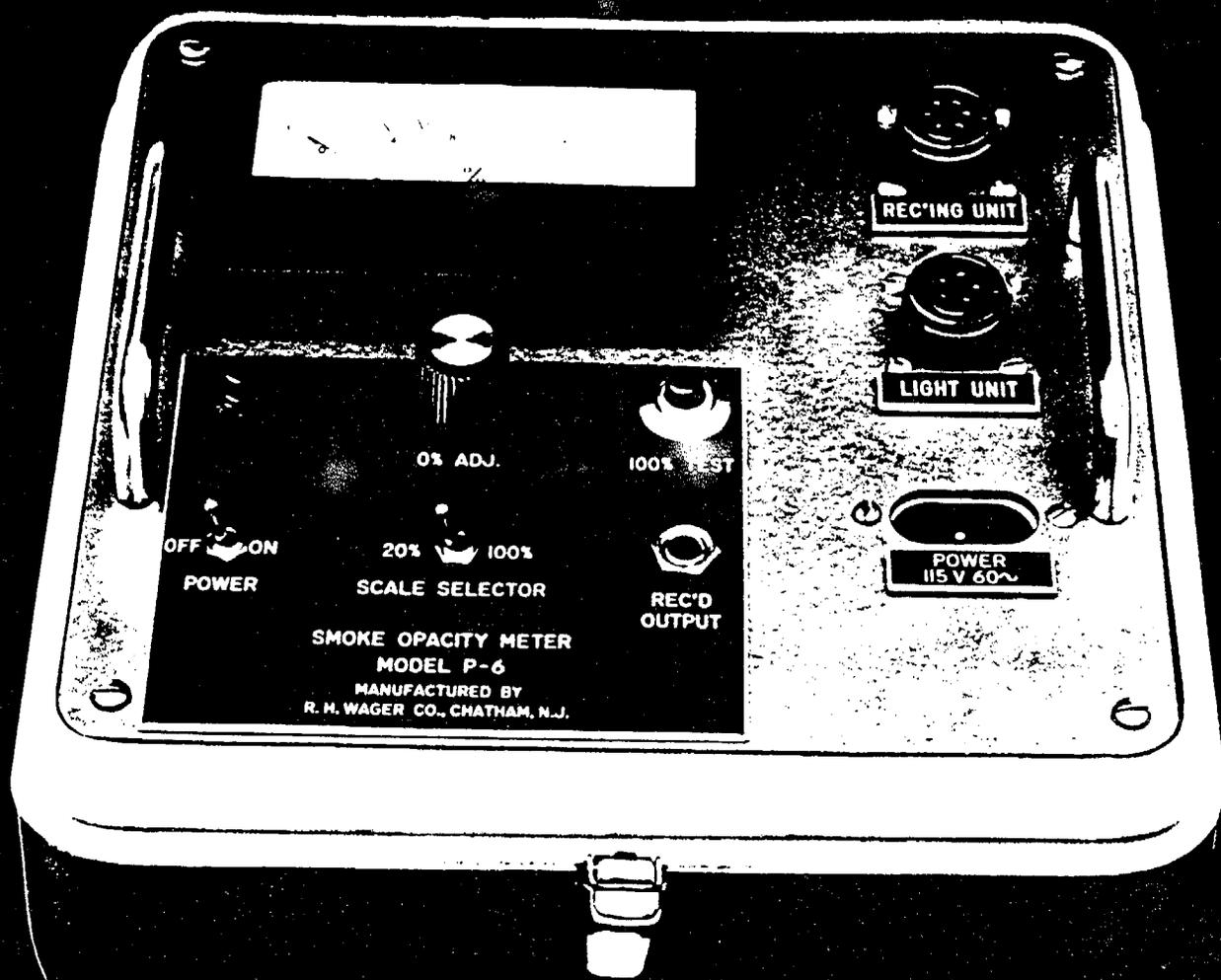
From left to right, Ray Savage, Michael Wager, and Paul Fern, of the Wager Co.

REPRINTED FROM

# DIESEL PROGRES NORTH AMERICAN

For further information, contact:  
**Robert H. Wager Co., Inc.**  
Passaic Avenue  
Chatham, New Jersey 07928  
201-635-9200

# TRUE, PRECISE SMOKE EMISSION READINGS— EVEN IN AMBIENT LIGHT.



THE WAGER PHOTOELECTRIC SMOKE OPACITY METER (P-6 Series)

# SMOKE OPACITY METER

## P-6 SERIES

### PURPOSE AND FUNCTION:

The Smoke Opacity Meter is a photoelectric device which was designed to provide an accurate means of detecting and measuring the opacity of smoke being emitted from a stack or exhaust opening. A pulsed light source enables the system to measure accurately even under ambient light (daylight or artificial) conditions.

The measurement of the opacity of the exhaust gas is accomplished by passing the exhaust plume between a light source and a photo sensitive receiver unit with the resulting smoke density appearing as a percent opacity on a meter. This meter will have one or more expanded scales to indicate very small amounts of opacity.

### GENERAL DESCRIPTION

The Wager monitoring system consists of a Light Unit which provides a source of illumination for the sensor cell; a Receiving Unit which houses the sensor cell; a Control Unit which contains the electronic circuitry, calibrating devices and meter to visually display the smoke opacity; the connecting cables to tie these units together and an air purge and/or water cooling system suitable to the specific installation.

The stack hardware may be supplied in several configurations (see illustrations and data, facing and back pages.)

The Control Unit may be supplied in either a lightweight, portable, weatherproof, fiberglass enclosure or as a standard 5¼" relay rack panel.

Optional equipment which may be required are Damper Units for positive shut off at the 4" stack nipples for maintenance purposes, Air Purge Blowers where compressed air is unavailable or undesirable, Mounting Frame to hold the stack units over the exhaust plume where a permanent installation is not required.

### QUICK REFERENCE DATA

MANUFACTURER \_\_\_ Robert H. Wager Co., Inc.  
Passaic Avenue  
Chatham, N.J. 07928 USA

TYPE \_\_\_\_\_ Smoke Opacity Meter

MODEL \_\_\_\_\_ P-6 Series

#### POWER

REQUIREMENTS \_\_\_ 120 VAC 60Hz, 0.5 Amp

### PERFORMANCE SPECIFICATIONS

Range \_\_\_\_\_ 0-20% — 0-100% Opacity

Warm Up Time \_\_\_\_\_ 10 minutes

#### Meter Response

Time \_\_\_\_\_ 2.0 Sec.

Approx. 0-90% Opacity

Resolution \_\_\_\_\_ 2% from 0-100% Opacity

Linearity \_\_\_\_\_ 2% from 0-100% Opacity

Zero Stability (Drift) Less than 1% in ten hours

#### Temperature

Compensation \_\_\_\_\_ Sensor elements  
electronically compensated  
25°F to 140°F

### ELECTRICAL SPECIFICATIONS

Light Source \_\_\_\_\_ Light emitting diode —  
Green Gallium Phosphide  
570NM

Light Sensor \_\_\_\_\_ Silicon Photo Diode

Connecting Cables \_\_\_ As required

Meter \_\_\_\_\_ 0-1 milliammeter  
Ruggedized Jewel  
Movement

Meter Accuracy \_\_\_\_\_ 1% Full Scale

Recorder Output \_\_\_\_\_ 0 to +10 VDC

### COMPLIANCE

All Model P-6 Series Meters, which come with 1-year warranty, meet EPA spectral and existing and proposed ISO and SAE specifications.

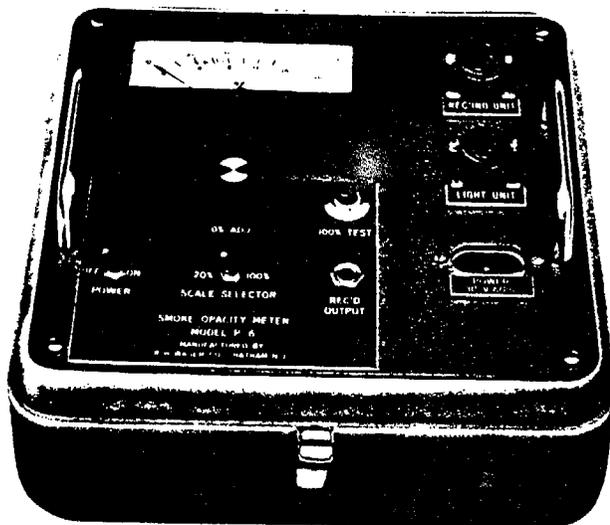
## FEATURES

- All solid state electronics
- Light source — green LED in photopic range — long life.
- Light source pulsed so electronics can discriminate between source light and ambient light, thus allowing unit to operate in direct sun or artificial light. All readings are to within 1% accuracy on a scale of 0-100%.
- Improved detector circuitry for high level DC transmission to control station, thus allowing long leads between detector and control unit.
- Test points provided in both Light and Receiving Units so alignment of system can be done at these units with a Simpson 260 multimeter (or equal) without having to see meter on control unit.
- All electronic components are Mil. Spec.

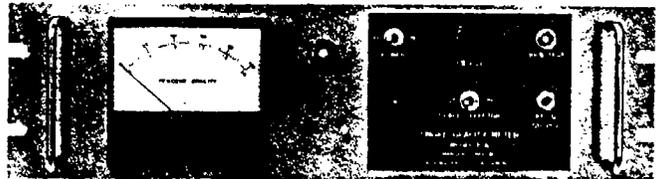
## MODELS: P-6 SERIES

### CONTROL UNIT

All Model P-6 Series Monitors, except the P-6P, may be supplied with either Portable or Rack Mounted Control Units, as illustrated.



**Portable:** The control panel is supplied in a lightweight, weatherproof, fibreglass case.



**Rack Mounted:** The control panel is supplied as a standard 5 1/4" relay rack panel for easy mounting.

The Wager Control Unit, Portable or Rack Mounted, displays smoke opacity read-outs on two scales, 0-100% and 0-20%. The Control Unit also provides analog output for chart recorder or computer.

## MODEL P-6

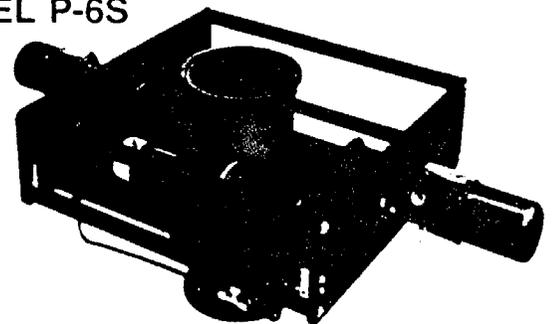


**STACK MONITOR:** Fixed Stack Monitor, as illustrated. The P-6 was designed particularly for large stack installations with 4" pipe nipples.

**CONTROL UNIT:** Portable or Rack Mounted.

**OPERATING RANGE:** 2 feet (min.) through 40 feet (max.)

## MODEL P-6S

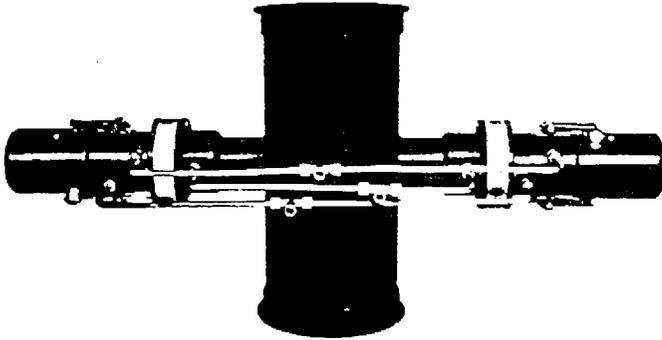


**STACK MONITOR:** Retractable Stack Monitor. This monitor slides into stack for read-out; after read-out, may be moved back to "zero" pipe position. This permits calibration to be checked while engine is on line. This retractable feature also prolongs monitor life.

**CONTROL UNIT:** Portable or Rack Mounted.

**OPERATING RANGE:** 4" through 10" diameter stacks.

## MODEL P-6IL



**STACK MONITOR:** In-Line Monitor, as illustrated; designed to mount as an integral part of the exhaust stack with the source and receiver units installed on a section of pipe equal in size to the diameter of the stack. Equipped with aluminum water-cooled chambers, air purge flanges, and insulating blocks to protect the unit's electronics against excessive heat.

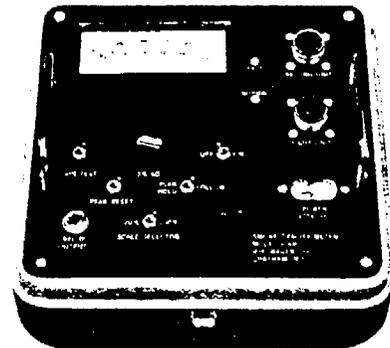
**CONTROL UNIT:** Portable or Rack Mounted.

**OPERATING RANGE:** 2" through 18" diameter stacks.

## MODEL P-6P



**STACK MONITOR:** The light and receiving unit are attached to a portable yoke which clamps to exhaust stacks of any configuration.



**CONTROL UNIT:** Portable, powered by rechargeable battery. "Peak hold" feature shows largest opacity reading.

**CABLE:** 25 feet in length, allows complete mobility in test areas.

**OPERATING RANGE:** Fixed operating distance of 7".

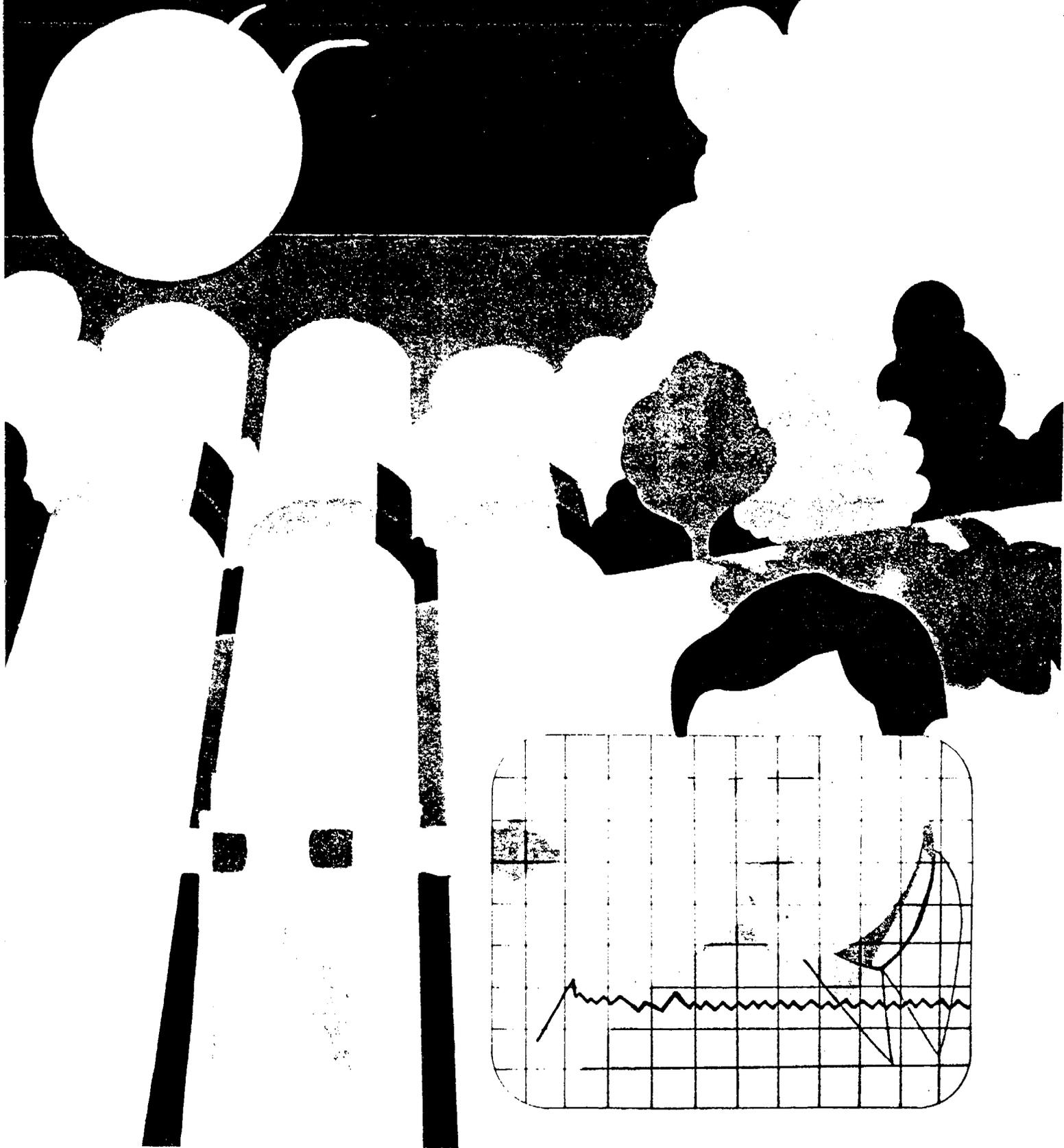
For additional details:

# WAGER

Robert H. Wager Co., Inc.  
Passaic Avenue  
Chatham, NJ 07928 USA  
Tel: (201) 635-9200

# M-7A M-8A

Photoelectric Smoke Indicator System



# M-7A SMOKE INDICATOR

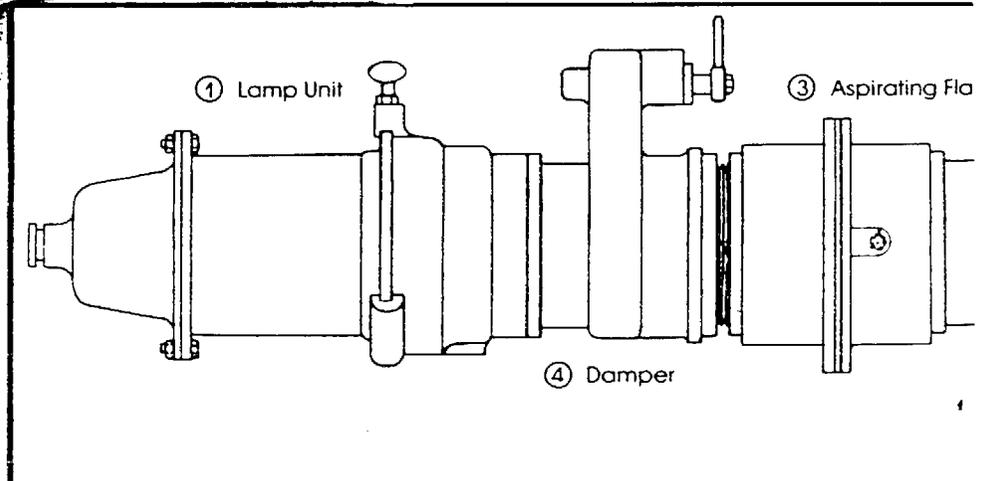
Differentiates  
between Black  
and White Smoke

M-7A Smoke Density  
Amplifier Cabinet

The M-7A Smoke Indicator was designed to provide an electronic means of detecting smoke density or opacity variations with the added ability to differentiate between White and Black smoke. The unit consists of photocells and two independent solid state operational amplifier circuits, one for indicating smoke density and the other, smoke color.

**The system consists of:** *Transceiver Unit* — whose function is twofold, first to provide a source of illumination for the photocell, and secondly, to house the white smoke detector cell. *Receiving Unit* — which houses the smoke density photocell. *Amplifier Cabinet* — which receives the signals from the photocells and provides the information display on a meter in percent opacity and indicating lights revealing smoking conditions as well as differentiating color.

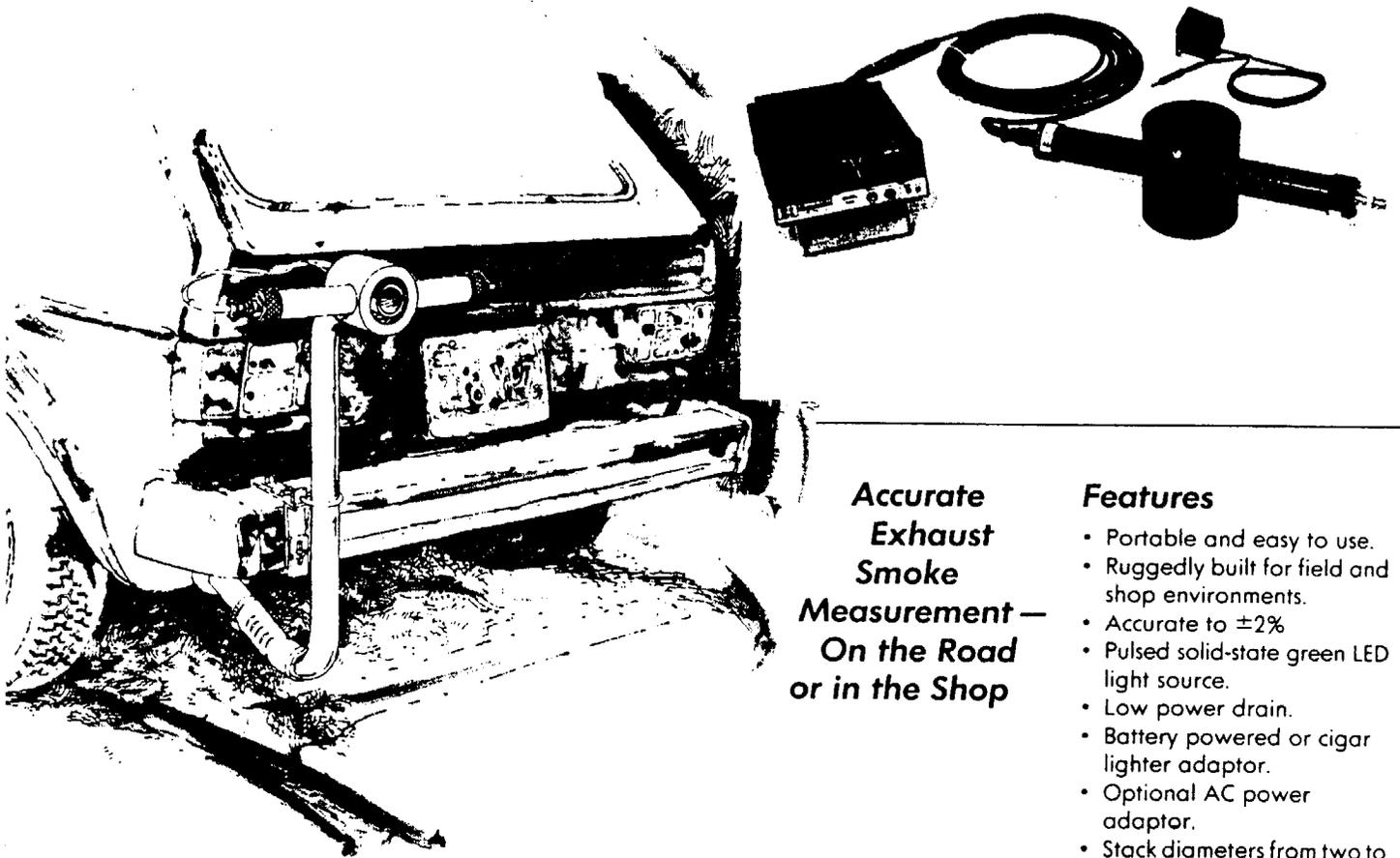
Photoelectric Unit





# Portable Opacity Meters

## Model 200

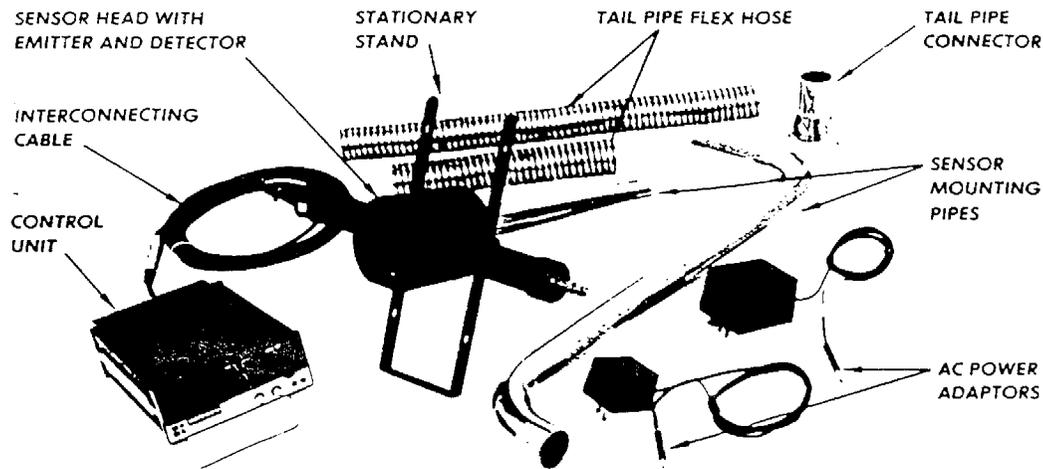


**Accurate  
Exhaust  
Smoke  
Measurement —  
On the Road  
or in the Shop**

### Features

- Portable and easy to use.
- Ruggedly built for field and shop environments.
- Accurate to  $\pm 2\%$
- Pulsed solid-state green LED light source.
- Low power drain.
- Battery powered or cigar lighter adaptor.
- Optional AC power adaptor.
- Stack diameters from two to six inches.
- Recorder output.
- $3\frac{1}{2}$  digit liquid crystal display.
- Reasonable cost.

# Portable Opacity Meters Model 200

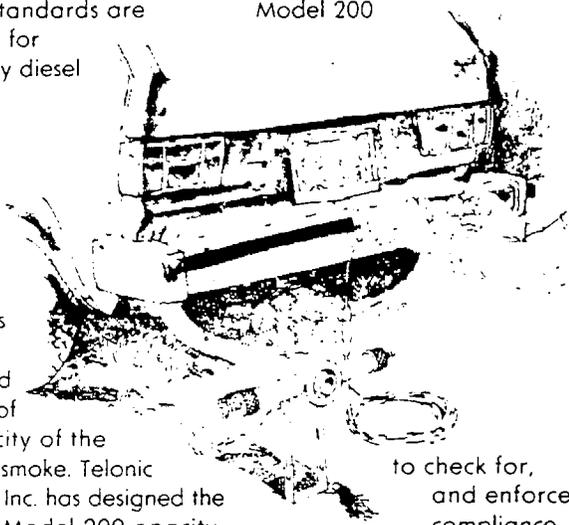


## Model 200 is the Standard

Federal regulations have established a quality level for diesel exhaust emissions from new vehicle engines. State and local agencies enforce high standards for emission control while the vehicle is on the road. Similar standards are enforced for stationary diesel engines.

Diesel exhaust quality is usually expressed in terms of the opacity of the exhaust smoke. Telonic Berkeley, Inc. has designed the portable Model 200 opacity meter to provide an inexpensive, reliable, and accurate instrument for diesel exhaust monitoring. The diesel operator needs this instrument to assure that vehicle exhaust emissions comply with state and local regulations.

The vehicle maintenance team also needs the Model 200 to check for economical engine performance, because excessive smoke usually indicates a fuel-rich condition and higher operating costs. Environmental enforcement agencies also require the Model 200



to check for, and enforce, compliance.

The Model 200 has the accuracy and reliability to assure that measurements made are fair. Most major diesel manufacturers use the Model 200. The U.S. Army (Installation Support Division) has recommended the portable smokemeter to their facilities, and the U.S. Air Force uses it nationwide. It is the only portable opacity meter having a USAF Federal Stock Supply Number (4910-00-409-8588).

## Description

The Model 200 opacity meter consists of a sensor assembly and an indicator unit. Some models use a telescoping 8-foot handle which permits the operator to position the sensor head across the exhaust stream at the top of a vertical stack. A chain and spring assembly holds the sensor in position on horizontal exhausts, or on moving vehicles.

Other models permit the sensor assembly to be clamped onto the vehicle bumper through an exhaust pipe extension.

The indicator is a lightweight, hand-held unit which contains the direct-reading opacity meter, calibration controls, electronics and batteries. A 20-foot cable connects the sensor head to the indicator unit.

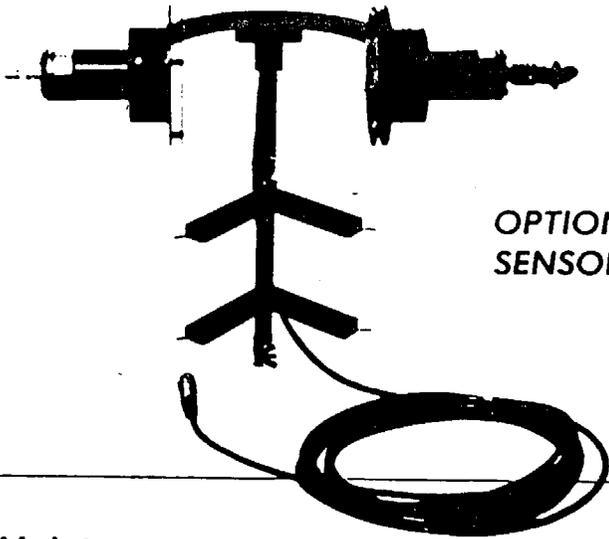
To use the Model 200, the operator adjusts the zero-set and calibration controls to set the meter zero and full-scale points. The sensor head is then positioned over the stack so that the exhaust stream passes between the light source (emitter) on one side, and the light sensor on the opposite side. The amount of emitted light attenuated by the smoke plume between the emitter and detector is the measure of smoke opacity. Ambient or reflected light does not affect the measurement. This

characteristic is achieved by pulsing the emitter at a high rate and using the "off" state as a reference for measuring detected light in the "on" state.

The light source is a pulsed, solid-state green light emitting diode which transmits light to a silicon photo detector. This system is identical to — and interchangeable with — our high accuracy, time-proven test cell, Model 107. The LED consumes only a fraction of the battery power that would be needed by an incandescent lamp system.

The Model 200 meets ISO and SAE specifications and exceeds EPA spectral specifications. It features an output jack which provides a d-c analog signal (0-100% range) to a strip chart recorder for road or dynamometer testing. The recorder provides a permanent record for further study in the laboratory.

Rechargeable nickel cadmium batteries can be installed and recharged as required. Nominal operation when using heavy duty type batteries is 10 hours. An adaptor is furnished which permits operation of the system from the vehicle d-c power by plugging it into the cigar lighter on the dashboard of the vehicle under test. An optional a-c adaptor is also available for operation of the Model 200 on 120-240 VAC, 50-60 Hz.



**OPTIONAL 6-INCH  
SENSOR HEAD**

**Maintenance**

The Model 200 is virtually maintenance-free. There is no incandescent lamp to replace, and the lens needs only periodic cleaning. The Model 200 is the ideal instrument for both environmental

compliance and diagnostic engine maintenance. An inexpensive, reliable instrument needing little care, it has been the choice of many government, industrial and military buyers.

**Specifications**

Range . . . . . 0-100% opacity  
 Accuracy . . . . .  $\pm 2\%$  full scale  
 Readout . . . . . 3½ digit liquid crystal display  
 Light Source . . . . . Light emitting diode (LED)  
 Light Receiver . . . . . Silicon photo detector  
 Spectral Output . . . . . 520-610nm, peak @ 570nm (green)

**Options**

- Stack Diameter . . . . . 4-inch or 6-inch sensor.
- Smoke Density . . . . . Converts opacity, 0-100% to smoke density  $K (m^{-1})$ .
- Gas Temperature Correction . . . . . Compensate smoke density,  $K (m^{-1})$  reading to standard 100°C gas temperature.
- Carrying Case . . . . . Houses digital readout unit, emitter and detector, and power adaptors.

**Recorder Output:**

Opacity . . . . . 10mv/%, 1 VDC F.S.  
 Smoke Density . . . . . 100mv/ $m^{-1}$ , 12 VDC F.S.

**Operating Temperature:**

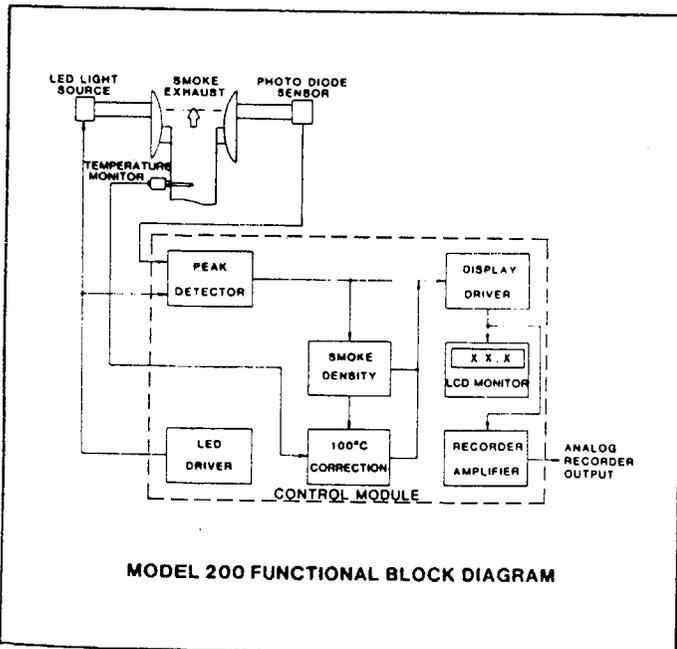
Control Unit . . . . . 5 to 50°C  
 Sensor Head . . . . . 0 to 50°C

Power Requirements . . . . . Four "D" size 1.5V batteries, or 12V adaptor which plugs into cigar lighter in vehicle, or an optional AC power adaptor.

Warm Up Time . . . . . 10 seconds  
 Response Time . . . . . 0.01 seconds to 90% of full scale  
 Drift . . . . . Less than 2.5% per hour  
 Meter Case . . . . . High impact plastic with aluminum covers.

**Mechanical Specifications**

	Size	Weight
Sensor . . . . .	6.5" x 11" x 3"	3.0 lbs.
Indicating Unit . . . . .	approx. 4" x 16" x 4.5"	4.5 lbs.
Interconnecting Cable . . . . .	approx. 20 feet	1.0 lbs.
Sensor Diameter:		
Standard . . . . .	2 inches	
Optional . . . . .	4 and 6 inches	

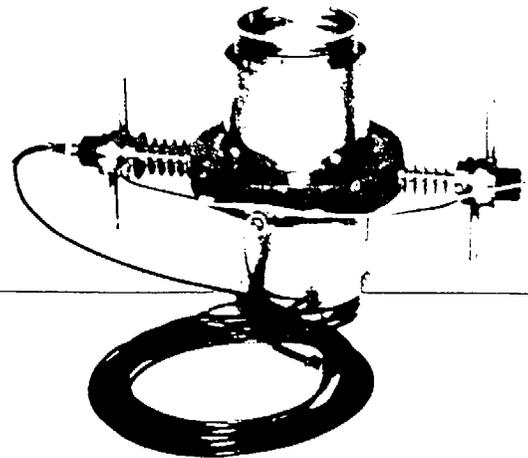




# TELONIC BERKELEY INC.

2825 Laguna Canyon Road  
Box 277  
Laguna Beach, CA 92652-0277  
TLX 18-2720 Domestic  
TLX 47-20277 Foreign

OUR TOLL FREE TELEPHONE (Except in California)  
(800) 854-2436 • IN CALIFORNIA (714) 494-9401



## Model 107 In-Line Opacity Meter

### Features:

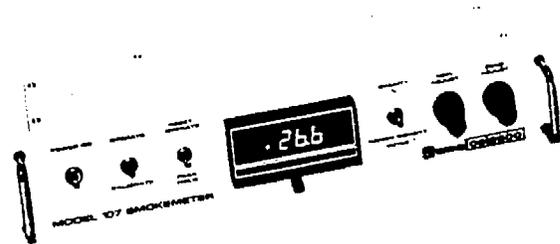
- Less Drift
- Rapid Transient Response
- Greater Precision
- $\pm 0.5\%$  Accuracy
- Improved Linearity
- Lower % Opacity Reading

For continuous, in line, full-flow smoke measurement. Designed for use in diesel engine test cells. Used by Cummins, Caterpillar, Detroit Diesel, Perkins Diesel and other major diesel engine manufacturers, Model 107 permits exhausting smoke outside the cell.

Assures measurement accuracy because smoke is

confined to fixed volume. Optical path length is also fixed, further insuring accuracy and repeatability.

- Meets requirements for diesel engine Federal test cycle.
- Measures opacity in the 0-100% Range
- Permanent solid-state light source
- For 6-inch stack (2- and 4-inch optional)
- Rack-mounted, all solid-state control unit
- Not affected by exhaust temperature or vibration
- Measures smoke density (K) in the 0-20  $m^{-1}$  Range



### Options Available

- Line Power..... 90 — 130 VAC or 180 — 260 VAC
- Linearity Calibration... In-situ linearity measurement with three neutral density filters in the range of opacity, 10%, 20%, or 40% nominal. Actual filter values traceable to EPA standards.
- Recorder Output..... 0 — 5VDC (0 — 100% opacity) 1 — 5VDC (0 — 100% opacity)
- Computer Interface... BCD output, 100/sec conversion rate
- ISO-Pak..... Meets ISO specification and includes: Temperature probe — TC shielded probe with TC connector and pressure tap.
- 100°C Correction..... Corrects K ( $m^{-1}$ ) smoke density to 100°C gas temperature.

### Specifications

#### Opacity Scale:

- Range..... 0 to 100%
- Resolution..... 0.1%
- Accuracy.....  $\pm 0.5\%$  opacity due to nonlinearity, 24 hour drift, etc.

#### Smoke Density K Scale:

- Range..... 0 to 20  $m^{-1}$
- Resolution..... 0.01  $m^{-1}$
- Accuracy..... 0.1  $m^{-1}$  to smoke density of 2  $m^{-1}$ ,  $\pm 5\%$  of reading above 2  $m^{-1}$

#### Response Time..... 0.01 sec to 90%

#### Readout..... 3-1/2 Digit Digital Display

- Recorder Outputs..... 10mV per % (1VDC at 100% opacity) 100mV per  $m^{-1}$  (optical density)

#### Light Source..... Light Emitting Diode

- Angle of Projection..... 99% within 3 degrees half angle
- Spectral Output..... 520 to 610 nm; peak — 570 nm
- Pulse Rate..... 600 Hz

#### Receiver..... Silicon Photodetector

- Angle of View..... 99% within 3 degrees half angle
- Spectral Response..... 400 to 1100 nm

#### Operating Temp:

- Control Unit..... 10 degrees to 50 degrees C
- Sensor Unit..... 70 degrees C Max Cell Ambient 800 degrees C Max Gas Temp
- Cooling Water..... 25 degrees to 45 degrees C

- Power..... 90 — 130VAC or 180 — 260VAC 50/60 Hz, 10 watts

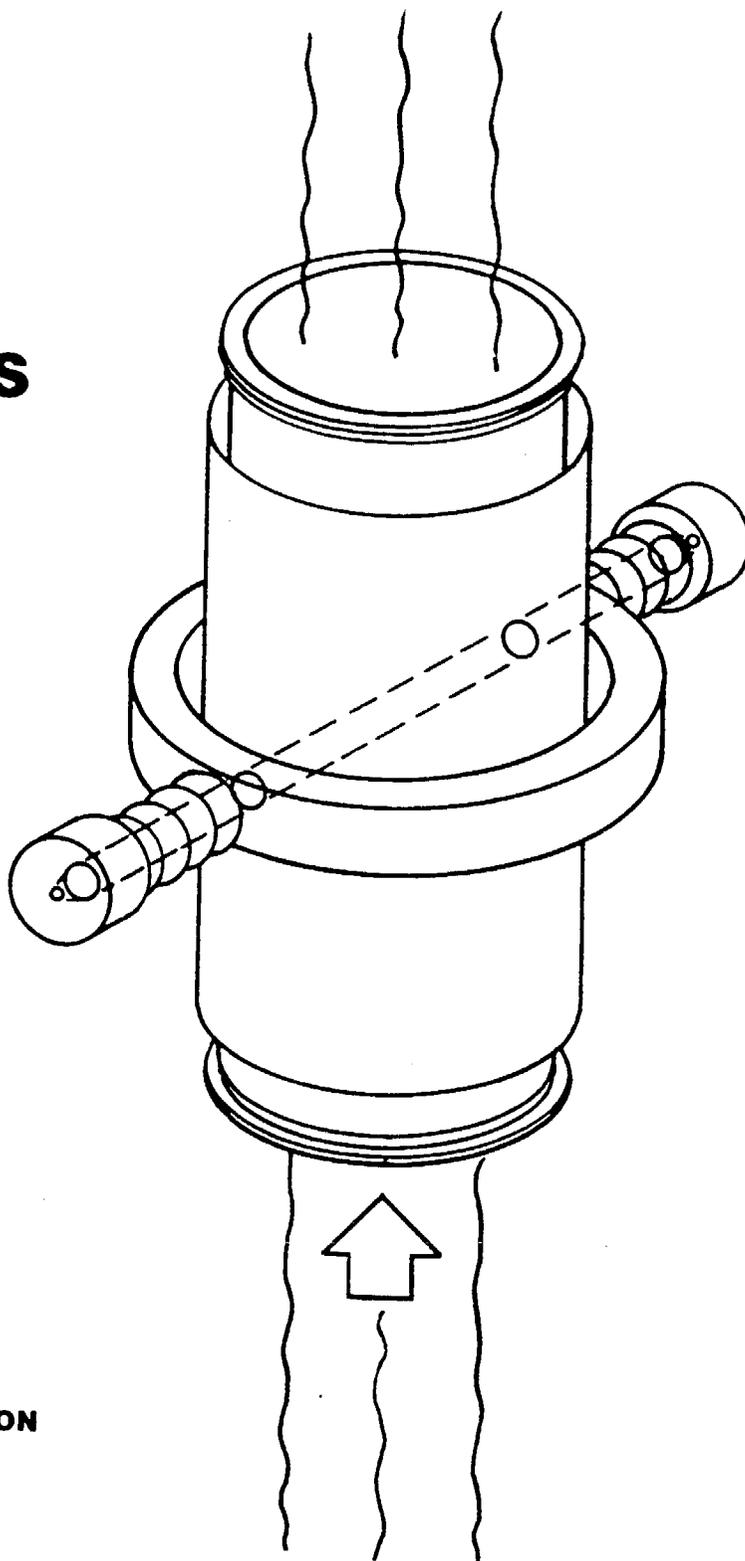
- Stack Diameter..... 6" 4" 2"

- Path Length..... 137mm 95.5mm 44.7mm

**celesco**

**BERKELEY**

**FULL-FLOW  
IN-LINE  
DIESEL  
SMOKEMETERS**

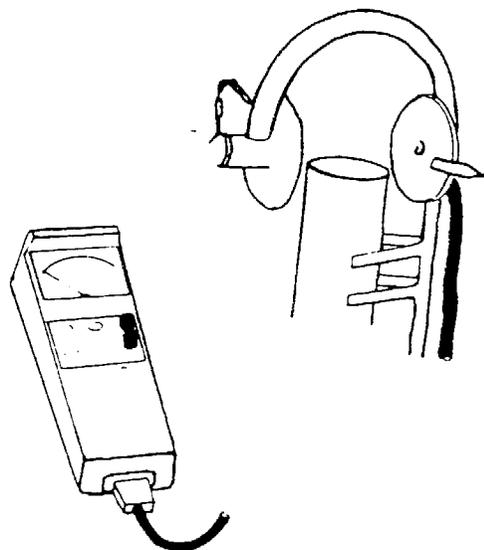


**DIESEL ENGINE INSTRUMENTATION**

by

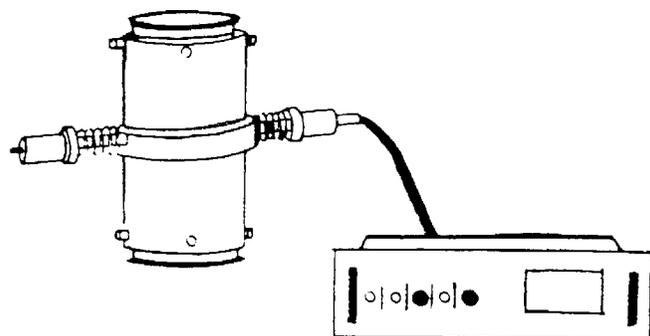
Celesco/Berkeley  
2700 Dupont Drive  
Irvine, California -- USA

## SMOKEMETER EXPERIENCE



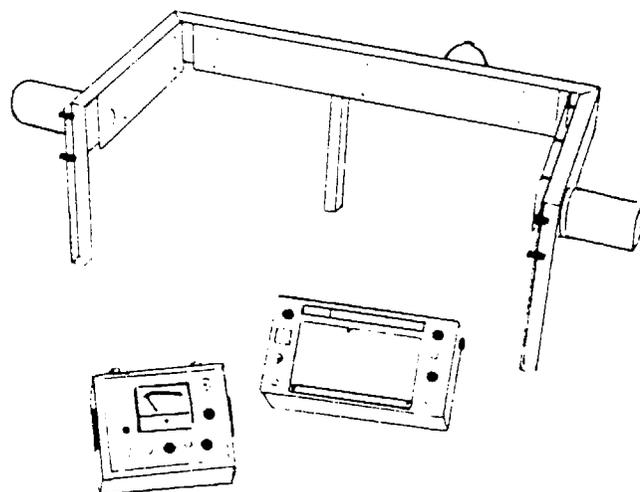
### Model 101

Intended for use on diesel truck exhaust pipes, these portable, battery operated, hand held smoke-meters are widely used both for emission compliance checking and for engine overhaul maintenance checks. Available with opacity reading (two ranges 0-100%, 0-20%) or smoke density K scale (two ranges, K scale dependent upon exhaust pipe diameter). Over 100 units at U.S. Air Force stations, standard unit for Cummins and Caterpillar overhaul centers.



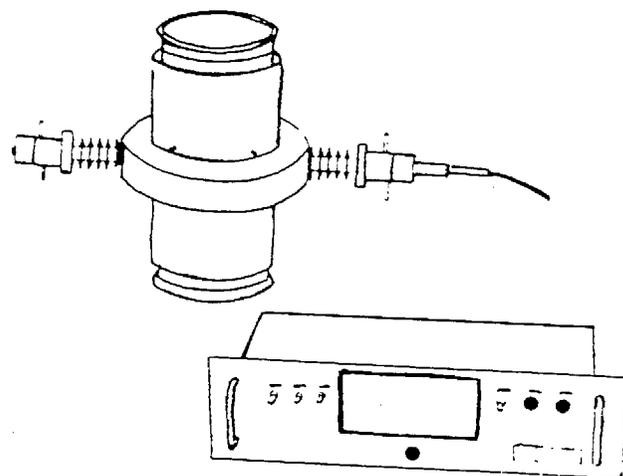
### Model 103

A standard for many years in the diesel engine industry. Over 500 units in test cells at Cummins, Caterpillar, John Deere, J. I. Case, Detroit Diesel, Allis Chalmers, Waukesha, International Harvester, Deutz Diesel. A full flow, in-line smokemeter using a pulsed red LED for long life, low maintenance. Extremely fast response attractive to engine development engineers.



### Model 105

Developed to meet the need of the railroad industry for a rugged top-of-engine smokemeter. Lightweight frame results in easy and safe installation at engine stack. Field tested at various railroad yards, this unit is approved by the American Railroad Association for use in engine smoke measurement.



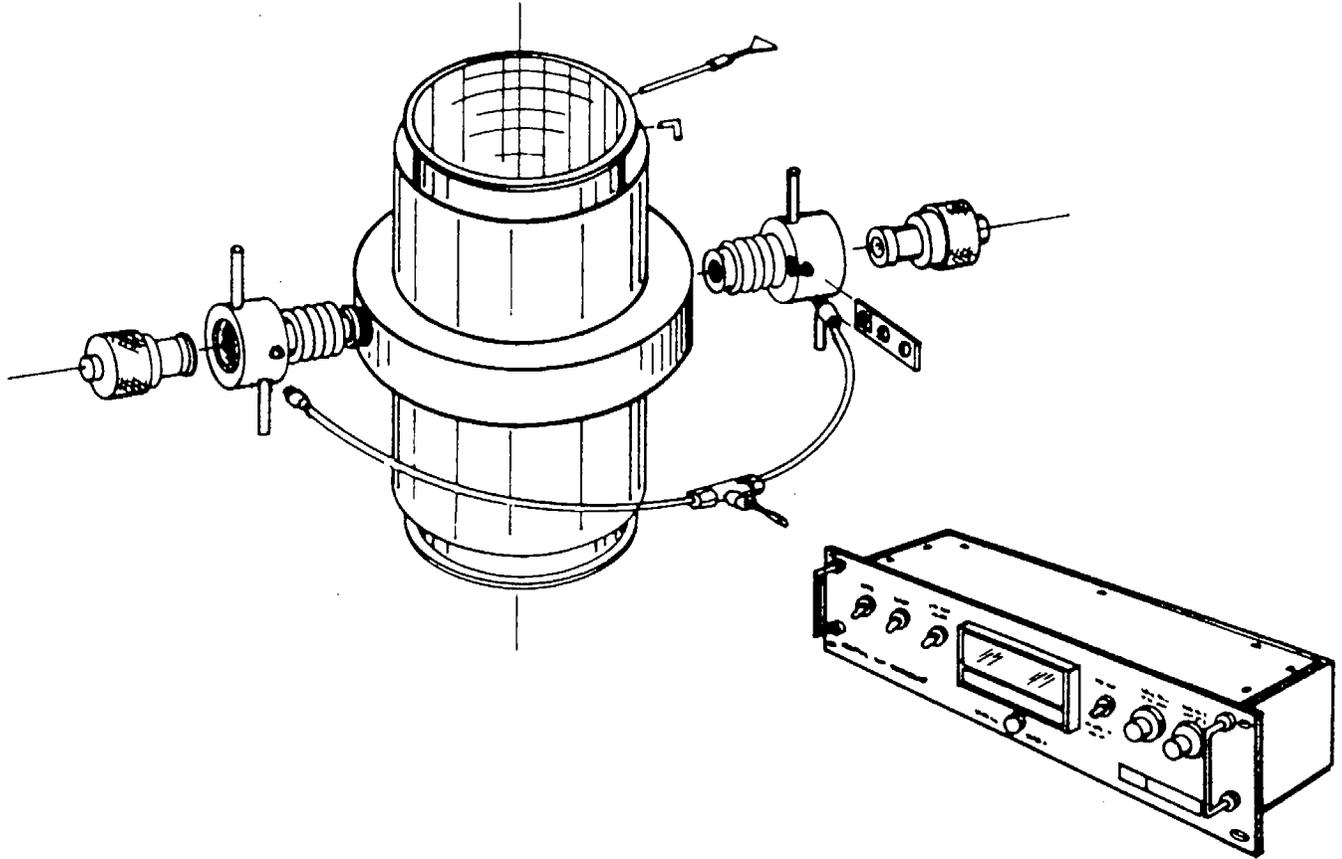
### Model 107

New in-line, full flow smokemeter designed to excel in stability with the ability to measure accurately down to 1% opacity. This unit meets and in most cases, exceeds all of the proposed ISO and SAE smokemeter specifications. New features include green LED, highly collimated optics, new electronics\* for exceptional system linearity, plus both opacity and smoke density readout. Extensively field tested, correlated with other smoke-meters including the PHS monitor.

\*Patent applied for.

# MODEL 107

## DESIGN DESCRIPTION



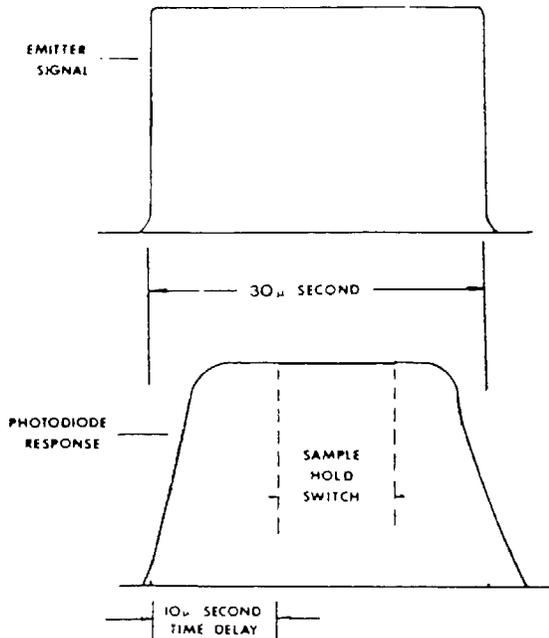
- Designed to meet ISO and SAE proposed specifications
- Light emitting diode used for emitter -- long life -- low maintenance
- Green LED used to meet ISO and SAE specs of emitter spectral characteristics
- Pulsed green LED emitter completely insensitive to ambient light variations
- Temperature compensated emitter/detector sets -- for low zero drift
- Highly collimated optics -- 0.1% view outside 3° half angle, 1% projected outside 3° half angle
- Optical filter attachment for in-stack calibration using neutral density filters
- Lens protecting purge air system -- wide pressure range without affecting smoke reading
- Gas pressure and temperature sensing capability if desired.
- Unique electronic circuit\* results in deviation from linearity of <0.1%
- Ability to read opacity or smoke density on digital display (opacity to 0.1%, K to 0.01) and as analog voltage recorder outputs
- Peak hold feature if maximum smoke reading desired
- Filter override to speed calibration

\*Patent applied for.

## PRINCIPLE OF OPERATION

The purpose of the smokemeter is to measure a characteristic of the engine smoke emission inherently related to smoke observed by the human eye. The fundamental characteristic that determines the obscuration of light produced by smoke is the effective particle concentration, which is termed smoke density, optical absorption coefficient or K factor. This parameter is not independently measurable, however the opacity of the smoke, i.e., the

percentage of a light beam attenuated along a known light path length, can be measured and the smoke density calculated electronically.



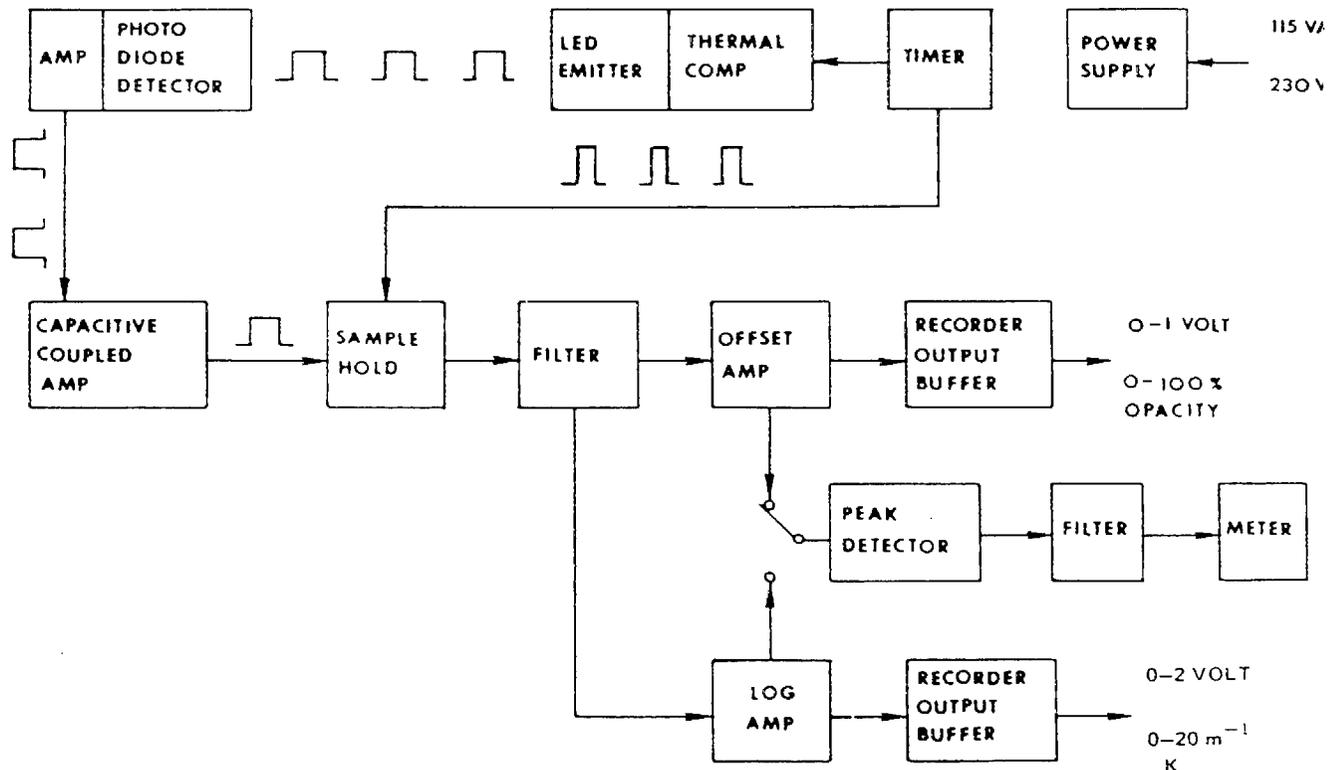
An optic system consisting of a LED light source, a collimating lens to project the light through the smoke stream, a focusing lens and photodetector is used to determine the light attenuation produced by the smoke.

To avoid any effects of ambient light variations on the photodetector, a rapidly pulsed light system is employed with a capacitively coupled circuit which ignores signal level changes other than the pulse train.

The LED is pulsed by an IC timer and the smoke attenuated light pulses are linearly converted by the photodiode into an electrical pulse.

The photodiode pulses pass through the capacitively coupled input amplifier to the sample hold circuit.

A second IC timer opens a sample hold switch which allows a clean portion of the photodiode signal to pass. The signal amplitude is held until it is updated 1.6 msec later by the following pulse. This signal is now an analog of the transmitted light intensity and after filtering and offsetting enters the buffered recorder output and the digital meter for display. The analog signal also is circuited to an IC logarithmic amplifier which converts the attenuation signal into the K factor, i.e., smoke density, for digital display and recorder output. This technique results in exceptional system linearity.



## COMPLIANCE WITH ISO PROPOSED SPECIFICATIONS\*

ISO	M107												
<p>The indicator of the opacimeter shall have a measuring scale graduated in units of light absorption coefficient from 0 to 5 m<sup>-1</sup> at least.</p> <p>The effective path length is determined taking account the possible influence of devices for protecting the light source and receiver.</p> <p>The indicator shall allow a light absorption coefficient to be read between 0 and 3 m<sup>-1</sup> with a precision of 0.5 m<sup>-1</sup> at least.</p> <p>The measuring device shall allow the maximum opacity to be stored for at least 5 sec. This value shall not decay by more than 1% during this time.</p> <p>The combined spectral response of the light source and receiver should be such that it lies between 400 and 700 nm and both the maximum response and the median of the area beneath the response curve should lie between 550 and 575 nm.</p> <p>The rays of the light beam are parallel within 3° to optic axis.</p> <p>The receiver does not take into consideration the direct or reflected light rays with an angle of incidence greater than 3° to the axis of the optical device.</p> <p>Linearity of Smokemeter</p> <p>Electric response time — time between the moment when the light is sealed off in less than 0.01 s and the moment when the device recording the measuring signal reaches 90% of the level of its final signal.</p>	<p>0 to 19.99 m<sup>-1</sup></p> <p><math>L_{\text{eff}} = 146 \text{ mm}</math></p> <p>May be read to 0.01 m<sup>-1</sup></p> <table style="margin-left: auto; margin-right: auto;"> <thead> <tr> <th style="text-align: center;">T°C</th> <th style="text-align: center;">DECAY</th> <th style="text-align: center;">TIME-SEC</th> </tr> </thead> <tbody> <tr> <td style="text-align: center;">4</td> <td style="text-align: center;">1%</td> <td style="text-align: center;">80</td> </tr> <tr> <td style="text-align: center;">50</td> <td style="text-align: center;">2%</td> <td style="text-align: center;">60</td> </tr> <tr> <td style="text-align: center;">56</td> <td style="text-align: center;">2%</td> <td style="text-align: center;">55</td> </tr> </tbody> </table> <div style="text-align: center;"> </div> <p style="text-align: center;"><math>\lambda</math></p> <p>Electrical circuit responds only to LED pulses. Total system response well within ISO maximum response range.</p> <div style="text-align: center;"> </div> <p>Only 1% of light projected beyond 3° half-angle. Only 0.1% viewed by photodetector beyond 3° half-angle.</p> <p>&lt; 0.1% deviation from linearity</p> <p>Rise time to 90%, 96 msec</p> <p>Fall time to 10%, 97 msec</p>	T°C	DECAY	TIME-SEC	4	1%	80	50	2%	60	56	2%	55
T°C	DECAY	TIME-SEC											
4	1%	80											
50	2%	60											
56	2%	55											

\* The ISO working group on smoke measurement has reached agreement on a tentative smoke-meter instrument specification (Draft International Standard 3173 with later alterations). The final ISO specification is expected to have similar wording.

**CELESCO/BERKELEY MODEL 107  
DEVELOPMENT AND EVALUATION TEST PROGRAM**

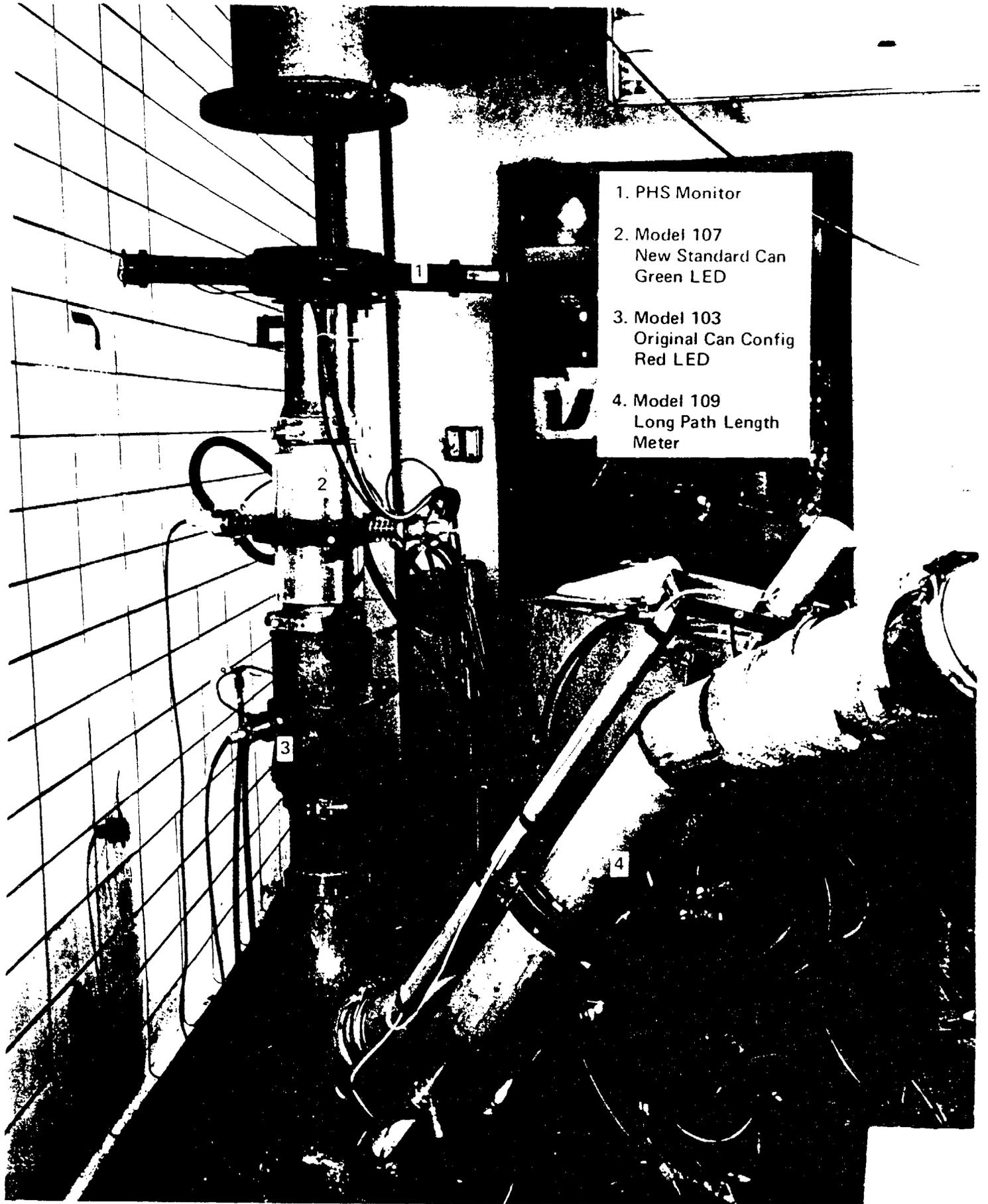
The new Model 107 Smokemeter was designed to meet the unique needs of today's diesel engine test engineer – reliable, repeatable smoke measurement in real time at very low smoke density levels, i.e., opacities of near 1 to 2%.

Rigorous test and evaluation of the Model 107 Smokemeter in the actual harsh test stand environment was required to insure the Smokemeter's superior performance. Eighteen months of development and tests have led to the Model 107 Smokemeter, which meets the demands of the engineer and is in compliance with the anticipated or recommended international specifications.

The following pages describe the M107 test programs and illustrate its capability. Testing was accomplished at various test facilities in this country and in the United Kingdom. The assistance of personnel at the various test facilities used for the M107 evaluation is greatly appreciated.

The mention of company or institution names of test facilities employed for test purposes does not constitute endorsement or recommendation for use of the Celesco/Berkeley Smokemeter by these organizations.

# TEST SETUP FOR CELESCO/BERKELEY OPACITY CORRELATION TESTS

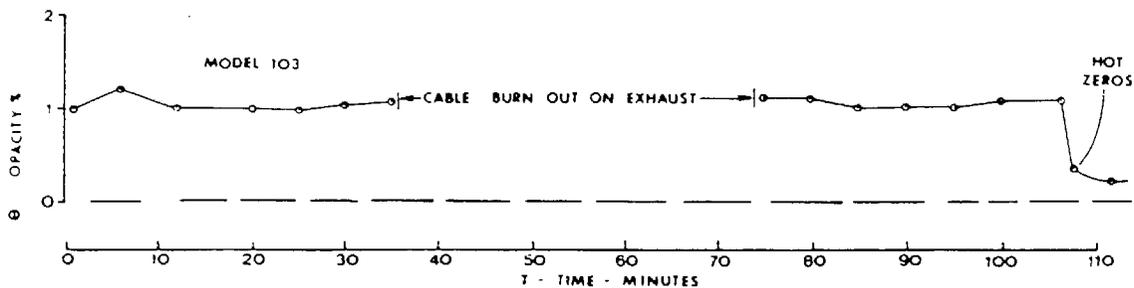


1. PHS Monitor
2. Model 107  
New Standard Can  
Green LED
3. Model 103  
Original Can Config  
Red LED
4. Model 109  
Long Path Length  
Meter

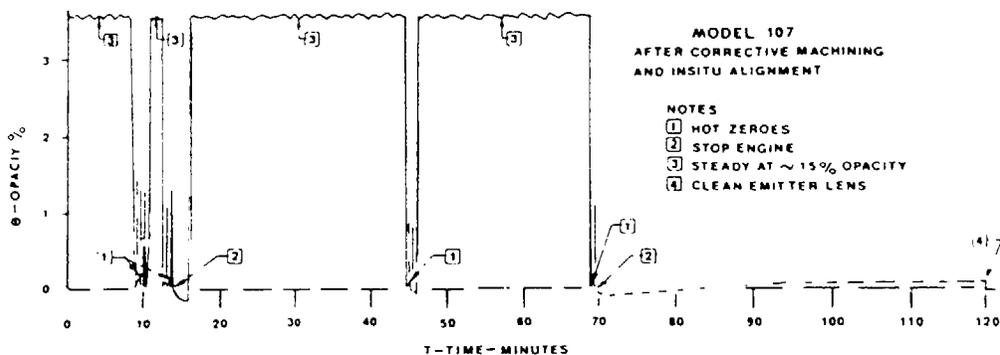
## TEST RESULTS

### Long Term Zero Drift Over Wide Temperature Range

A series of tests at various facilities was performed to determine long term drift characteristics and thus ability to measure very low smoke densities accurately.



Test No. 1 was performed at Cummins Tech Center, March 1976. The hot zero after 108 minute test run was in error by 0.34% opacity reading.

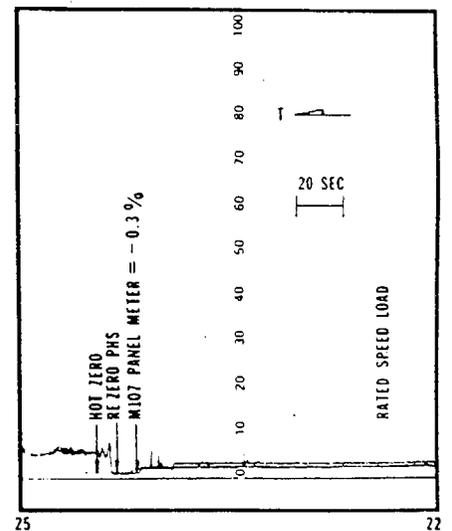
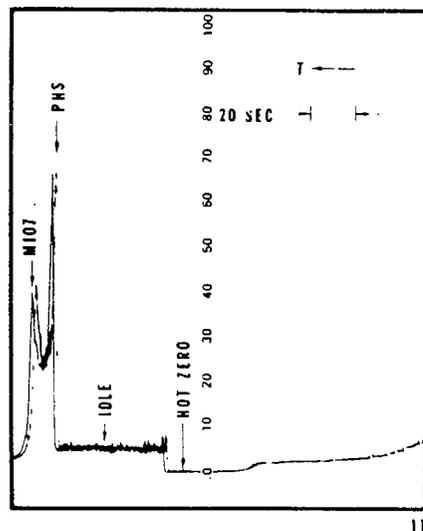
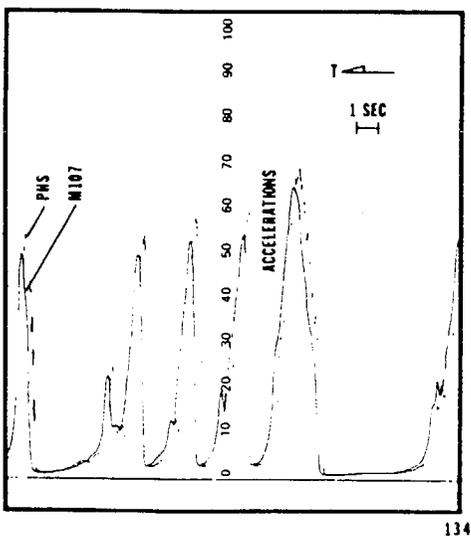
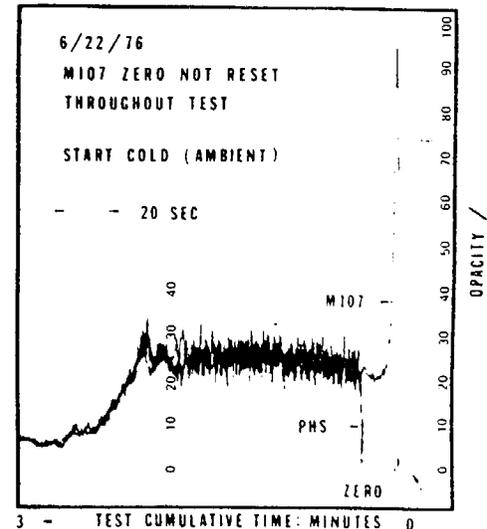
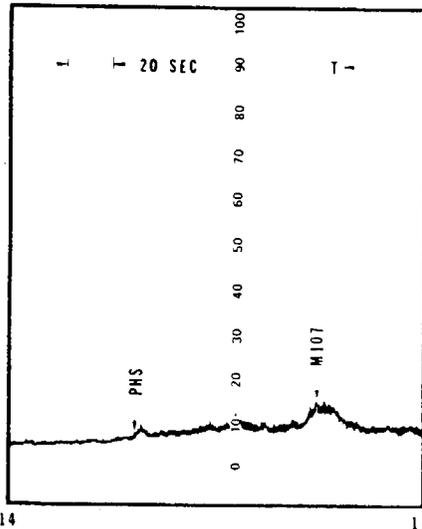
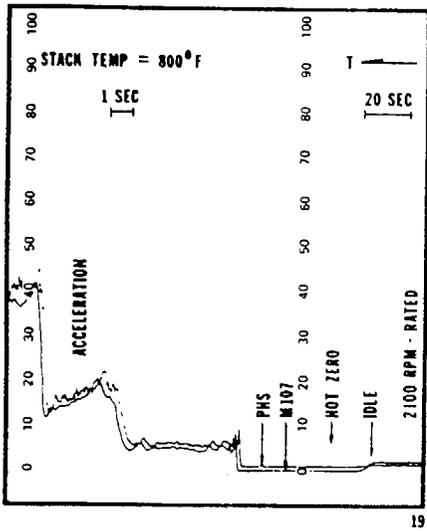


Test No. 2 was performed at Celasco's San Diego plant, April 1976. Final zero at end of test was in error .05% opacity reading. Emitter/Detector set carefully aligned. Exhaust stack temperature limited to 500°F.

Test No. 3 was performed at Cummins Tech Center, April 1976. The test setup was similar to the previous Cummins test cell arrangement, however, only the M107 and the PHS monitor were installed for testing. The PHS monitor was positioned approximately 3" above the exhaust pipe exit. The M107 was installed approximately 24" upstream of the exit.

The transient response of the M107 observed in the chart records is slowed by the electronic filter. A tenfold increase in response is obtained by bypassing this filter.

The M107 and PHS Smokemeters were zeroed at cold (ambient) temperature. The M107 zero was not adjusted throughout the approximately 4 hour test. The PHS was rezeroed once after a 'hot zero' test indicated 1% drift. During the test which included engine operation through warmup, idle, acceleration, rated speed etc., the stack temperature at the M107 Smokemeter location exceed 800°F. MAXIMUM ZERO DRIFT OF THE M107 FOR THE ENTIRE TEST WAS ONLY 0.3%.



**TEST RESULTS**  
**MOTOR INDUSTRY RESEARCH ASSOCIATION – JULY, AUG. 1976**

Tests were performed at the Motor Industry Research Association (MIRA) in Nuneaton, United Kingdom during July and August of 1976. Purpose of the test was to demonstrate accuracy, repeatability and low thermal drift characteristics of the M107 during typical test stand engine runs.

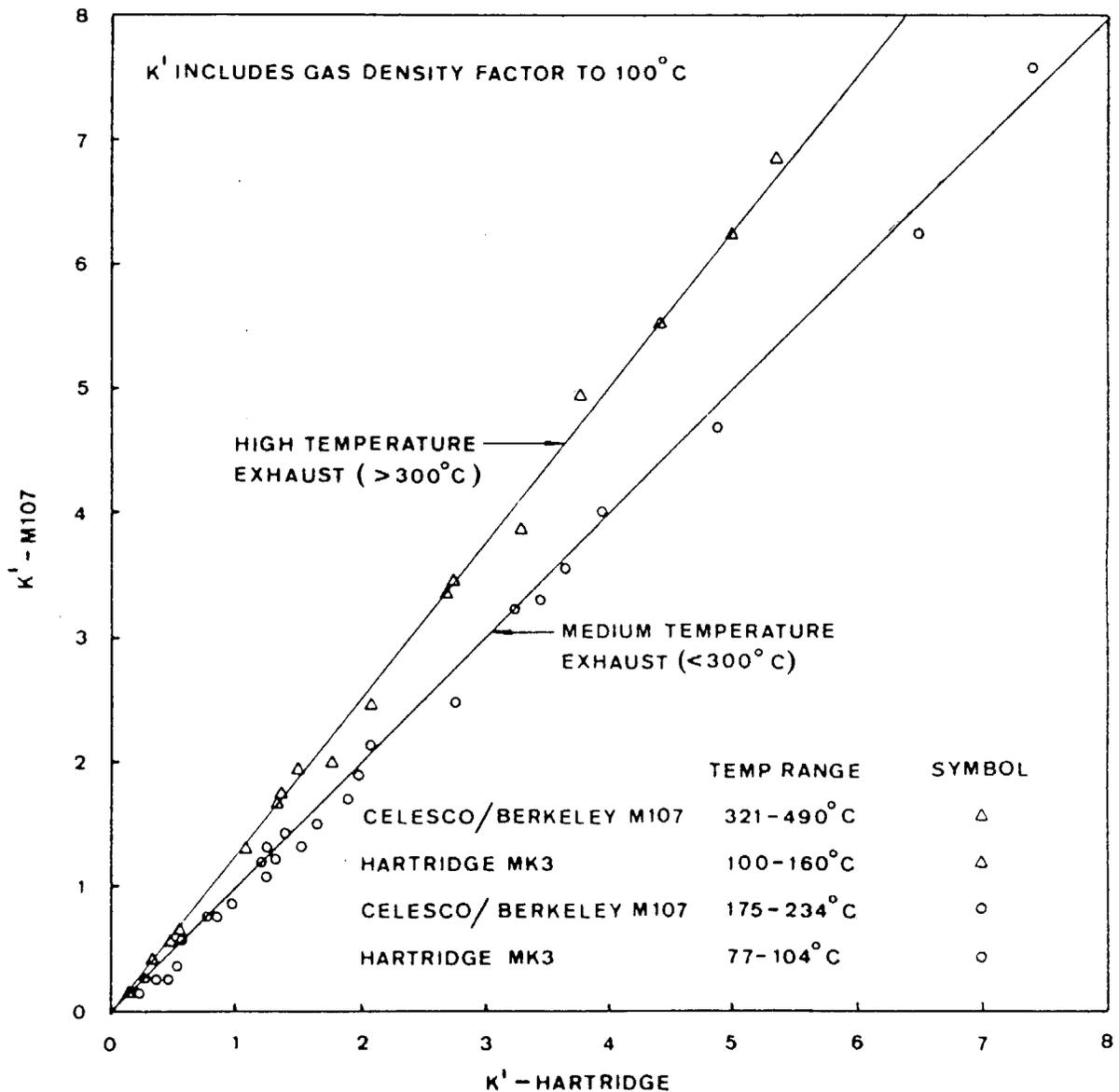
No general problems were encountered in the Smokemeter operation and the instrument's performance with regard to zero stability was exceptionally good.

Smoke opacity measurements were taken simultaneously with the M107 and a Hartridge MK3 Smokemeter. The smoke density,  $K$ , was calculated for both instruments and a Charles Law gas density correction factor to a gas temperature of  $100^{\circ}\text{C}$  was applied to facilitate data comparison of the two instruments which measure at widely different temperatures. The data is shown graphically for two exhaust gas temperature regimes – basically above and below  $300^{\circ}\text{C}$ .

Within the two gas temperature regimes there was an excellent linear relationship between the measurements of the two instruments. The difference in correlation for the hot exhaust case, i.e., above  $300^{\circ}\text{C}$ , and the lower temperature exhaust is relatable to effects other than gas density changes which occur in diesel smoke exhaust in the transition from high to low temperature.

These effects are primarily concerned with particle size distributional changes which occur as particle agglomeration takes place. Resultant changes in geometric mean diameters effect the extinction coefficient as well as the light obscuration area. These size distributional changes apparently occur in a narrow temperature zone near 300°C as reported by Vuk, Jones and Johnson of Michigan Tech. University.

The tests demonstrated that both instruments were measuring accurately the smoke particles in the exhaust gas stream they were examining. One to one correspondence between the two measurements is obtained only if all hot to cool temperature exhaust changes are considered.



## HIGH SPEED TRANSIENT TESTING

In tests with an evaluation M103 Smokemeter, Mr. Neil Cordell of Simms-Lucas demonstrated the high speed measurement capability of the full-flow in-line instrument. Using an oscillographic recorder, the short time opacity changes are shown to be the individual engine firing pulses. Deterioration of certain cylinder's performance with reduced engine RPM can be observed.

The M107 can be used for this analytical emission work by bypassing the electrical filter.

