Part 4

Environmental aspects

18

Exhaust smoke, measurement and regulation

Contents

18.1 General considerations

It has long been appreciated by engineers that the presence of smoke in the diesel engine exhaust is an indication of poor combustion resulting from some malfunction or maladjustment. Nevertheless, with increasing concern for the effect of air pollution on the environment, particularly in the field of road transport, vehicle exhaust emissions have, in recent years, been subjected to increasingly stringent regulations.

Most industrialized countries have therefore introduced regulations of varying degrees of complexity to control smoke emission from road vehicles. The regulations have been in addition to the relatively simple existing regulations covering industrial plant and have involved much development both of test methods and instrumentation.

Smoke may be defined as particles, either solid or liquid (aerosols), suspended in the exhaust gases, which obstruct, reflect, or refract light. Diesel engine exhaust smoke can be categorized under two headings:

1. Blue/white in appearance under direct illumination, and consisting of a mixture of fuel and lubricating oil particles in an unburnt, partly burnt, or cracked state.
2. Grey/black in appearance, and consisting of solid particles of carbon from otherwise complete combustion of fuel.

The blue component derives mainly from an excess of lubricating oil in the combustion chamber, resulting from deterioration of piston ring sealing, or value guide wear, and is thus an indication of a need for mechanical overhaul. However unburnt fuel can also appear as blue smoke if the droplet size is circa 0.5 μm.

The white component, on the other hand, is mainly a result of too low a temperature in the combustion chamber during the fuel injection period. It has a droplet size of circa 1.3 μm. This can occur as a transient condition during the starting period, in low ambient temperatures or at high altitude, disappearing as the engine warms up. On the other hand, it can result from too late fuel injection or may even be an indication of a design fault, in the sense that the compression ratio is too low, or has been optimized for an inappropriate combination of operating conditions.

Grey/black smoke is produced at or near full load if fuel in excess of the maximum designed value is injected, or if the air intake is restricted. In normal operation its onset is associated with reduced thermal efficiency and sets a limit to power output before any serious proportion of toxic component such as carbon monoxide is discharged. The main causes of excessive black smoke emission in service are either poor maintenance of air filters and/or fuel injectors, or incorrect setting of the fuel injection pump.

Such smoke consists essentially of carbon particles or coagulates of a wide range of sizes, ranging from 0.02 μm upwards to over 0.12 μm mean diameter. This size distribution depends to some extent on the type of combustion system, which also affects the onset of smoke emission as fuel input quantity is increased. Thus, in general, open chamber (direct injection) systems show a rather gradual increase in exhaust visibility with increasing fuelling, whereas swirl chamber (indirect injection) systems tend to have a critical fuelling level above which smoke emission increases very rapidly. It should be appreciated however, that there are some carbon particles present in the diesel exhaust under any operating conditions, so that zero smoke emissions is impossible.

Fuel properties are also capable of influencing smoke emissions. Thus, increasing the cetane number will reduce the tendency to produce white smoke, as also will increased volatility, usually indicated by reduction in mid-boiling point. On the other hand, chemical composition, cetane number and volatility all affect black smoke in a complex way, while increasing relative density will increase black smoke, for the same fuel pump setting, merely as a result of the increased mass of fuel injected. Compounds of the alkaline earths, typically barium, are effective as fuel additives, in small quantities, in reducing black smoke, but their use poses problems in administering regulations, as well as in fuel distribution, and they remain only of technical interest[1,2].

In seeking to control 'excessive' emission of smoke by regulation and inspection it is clearly not satisfactory to rely on subjective impression. Instrumentation is necessary to quantify smoke objectively as to its degree of visibility. It is also necessary to define a test method to relate the objective measurement to the subjective impression in a meaningful way.

Much early work on the optical properties of smoke plumes was carried out by the United States Public Health Service (USPHS) of the Department of Health, Education and Welfare[3]. This demonstrated, in viewing a stationary smoke stack in various conditions of lighting, and at different times of day, that the subjective visual assessment of identical plumes varied widely, particularly in the case of white smoke. The conclusion was reached that the optical property easiest to measure is the light transmittance of the plume.

18.2 Instrumentation

It would be quite impossible in the space available to describe the multitude of smoke meters and indicators that have been devised over the years. Only those which have achieved some common acceptance, or have been specified in connection with Standards or Regulations will therefore be considered in brief detail, as representing a generic type. These types fall into fairly well-defined classes.

18.2.1 Comparators

Typical of this class, in which comparison of the visual appearance of a smoke plume is compared directly with a standard scale of grey, is the Ringelmann Chart[4]. In this, a white card, on which has been printed a series of black grids obscuring, respectively, 20%, 40%, 60% and 80% of the surface, is viewed in optical proximity to the plume. The degrees of obscuration listed are arbitrarily numbered 1, 2, 3 and 4 Ringelmann. On this scale the white card is numbered 0 and a totally black card 5 Ringelmann.

Although there are obvious objections to comparing the appearance of smoke transmitting light from behind the plume with that of a chart reflecting light from a quite different part of the sky, the Ringelmann Chart has been in common use for external surveillance of industrial plant.

A preferable comparator would appear to be a photographic grey scale, having varying shades of blackness on a transparent base. With its use, the smoke can be compared against a similar background and with similar transmitted light. The grey scale can be accurately calibrated in terms of per cent transmittance and thus fulfils the recommendations of the USPHS referred to earlier. Even so, if the smoke is not black, errors can clearly arise. Various forms of this type of comparator are available, including the 'USPHS Film Strip'.

It will be obvious that such comparators are of very limited use in assessing smoke emission from a moving vehicle, with the constantly varying lighting, background and viewing angle, to say nothing of the varying emission from the vehicle itself, as speed and load change.

We wish to acknowledge the help of Ricardo Consulting Engineers in the updating of this chapter.

18.2.2 Filter-soiling 'spot' meters

If exhaust gas is passed through a white filter paper, the carbon particles are deposited, and the darkening of the paper can be taken as a measure of the smoke density. For consistency of measurement it is essential that a fixed volume of gas is passed through a defined area of filter paper, and the paper itself needs to be closely specified. The gas sample should be passed through the paper at a constant rate, and excessive pressure fluctuations at the point in the exhaust system from which the gas sample is extracted will produce erroneous results, as will condensation of moisture on the filter paper. Furthermore, it has been shown[6] that a high proportion of aerosols in the exhaust gives a reduced value of smoke density, since the paper is rendered transparent, to some extent. Such smokemeters are therefore of no use in cases where blue/white smoke is present.

The simplest usable form of this type of instrument is represented by the Bacharach Type RCC-B. This is a hand operated suction pump drawing an exhaust sample through a $\frac{1}{4}$ in sampling probe inserted $2\frac{1}{2}$ in into the stack. The stroke volume to filter area is 225 cu in per sq in (363 cc per sq. cm). The soiled filter paper, backed by a white plastic, is compared visually with a 10-step series of grey shades, ranging from 0 (white) to black (9).

The matching of the darkened filter to the steps of grey involves some degree of subjective judgement, while the manual operation of the pump is likely to lead to some error as a result of uneven rates of withdrawal of the sample. This instrument is really only of use in monitoring the smoke from boiler plants, and is not suitable for assessing diesel engine exhaust.

Probably the ultimate development of the 'spot' type of smokemeter is that developed in Germany by Bosch[7]. This Sampling Pump. Type EFAW/65, overcomes many of the objections raised above, and avoids the need for an external power source (*see Figure 18.1*). Before taking the sample, the pump piston is set manually in the inner (minimum volume) position and is held there by a spring-loaded ball detent. To take the sample this detent is remotely released pneumatically, permitting the piston to be returned by a spring to the outer (maximum volume) position, the movement being accomplished in 1 to $1\frac{1}{2}$ seconds. The volume displaced is 0.33 litres and the gas is drawn through a circular filter area of 8 sq. cm. It is mandatory that the sampling probe is that specified by the makers, as this is designed to prevent dynamic pressures at the sampling point being transmitted into the sample line and so affecting the pump piston motion. Static pressure at the sampling point should not exceed 15 in (380 mm) of water.

A detailed procedure has been laid down for the sampling operation[8], and this should be followed precisely if the results are to be consistent between different operators. At the same time, maintenance procedures on the sampling pump, and checks for leakage must also be carried out.

The darkening of the filter paper is assessed by means of an evaluating unit. Type EFAW/68 (*see Figure 18.2*). This is, in effect, a reflectometer, the light from a filament lamp being reflected from the soiled filter disc onto an annular photocell. Lamp, photocell and filter disc are arranged coaxially, the disc resting on a stack of at least twelve clean filters. The output from the photocell is fed to a microammeter, scaled arbitrarily from 0 to 10 Bosch Numbers. Again, a detailed procedure has been devised to ensure accuracy and consistency[8,19], including periodic checks for zero and linearity.

Use of the Bosch smokemeter is largely confined to test bed operation under steady state engine operating conditions, and it is clearly outclassed by more versatile instruments. Nevertheless, the sampling unit possesses the practical merits of robustness and mechanical simplicity, which enable it to endure the rigours of test bed use and operation by relatively unskilled personnel.

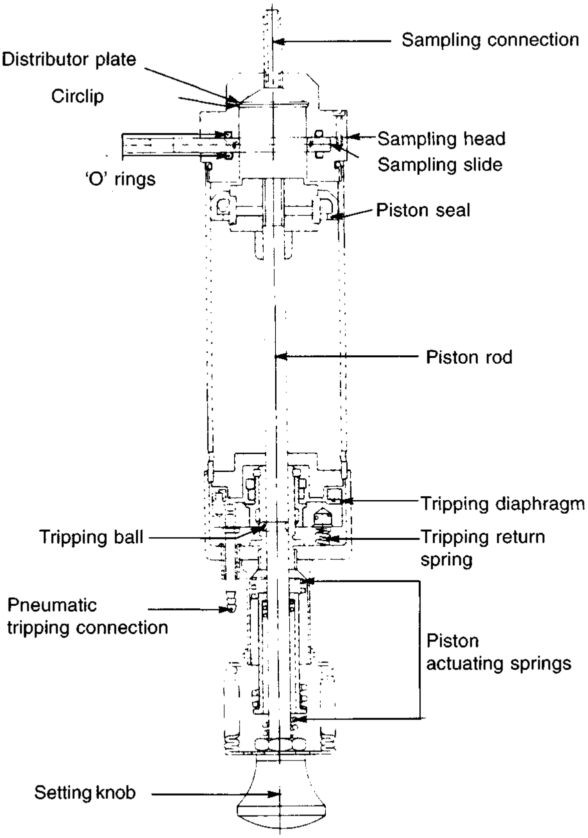

Figure 18.1 Bosch sampling pump-Type EFAW/65

The more delicate evaluating unit can be kept remote from the test area, can deal with the output from several sampling units, and provides a semi-permanent record. With increasing stringency of smoke legislation the Bosch is somewhat lacking in sensitivity to the lower levels of smoke density demanded. In a more elaborate and sophisticated form, with remote control, the various AVL meters—including fully automatic units—(designed and made by AVL Professor List, Graz. Austria) overcome many of the shortcomings of simpler units, giving high resolution and good repeatability. The AVL 415 smoke meter looks likely to become the new industry standard for engine development work. This unit is automated and is particularly sensitive at very low smoke numbers.

A variant of the sampling pump to meet an increasing requirement to assess smoke during a short period of full-load engine acceleration has also been devised. Named as an 'integrating' smokemeter the movement of the pump piston has been pneumatically damped so that it is extended to some 7 s, so that the carbon deposit on the filter is an average representation of the smoke emission over the acceleration period. The filter area is reduced to 1.1 sq cm and the smoke level is evaluated visually by use of the Bacharach Grey Scale referred to earlier. This form of sampling pump is designated Type EFAW/65B.

As mentioned earlier, and in common with all filter-soiling smokemeters, the Bosch meters cannot give useful or accurate results if there is appreciable blue/white smoke present in the exhaust.

18.2.3 Opacimeters

The visibility of smoke is by definition an optical phenomenon, and its density most easily measured in terms of light absorption

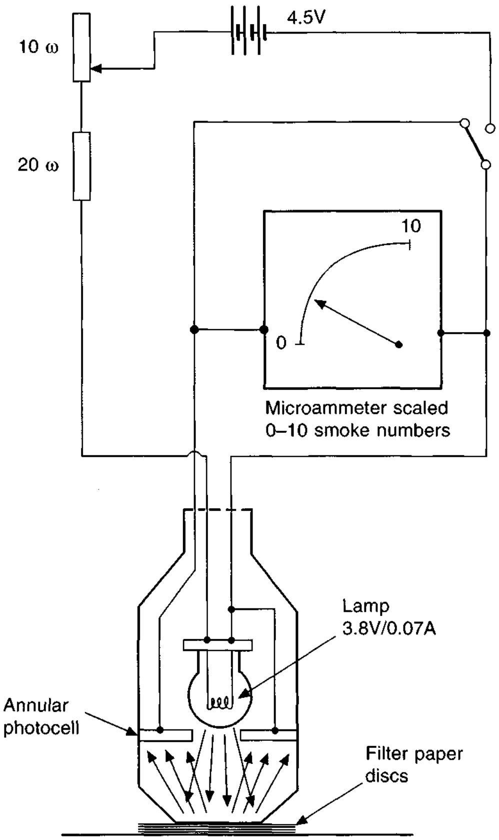

Figure 18.2 Bosch evaluating unit reflectance meter)—Type EFAW/68

either across the width of the flue through which the smoke is passing, or through a chamber into which a sample of the gas is diverted. The essential elements are therefore a light source, a defined length of light path filled with smoke, and a device (photocell) placed at the opposite extremity of that light path from the light source to convert the transmitted light into electrical current.

Photocell output is related linearly to the reduction in light intensity (opacity) resulting from the presence of smoke, and opacity is usually expressed as a percentage:

$$N = 100\left(1 - \frac{I}{I_0}\right) \text{per cent opacity} \tag{18.1}$$

where

I is the light intensity at the photocell with smoke present in the light path;

I_0 is the light intensity at the photocell with only clean air present in the light path.

The reduction in light intensity can be expressed in accordance with the Beer-Lambert Law as:

$$I/I_0 = e^{-naQL} \tag{18.2}$$

where

n is the concentration of smoke particles (for black smoke gm/cu m carbon);

a is the average particle projected area;

Q is the average particle extinction coefficient;

L is the effective light path length within the smoke (in meters).

Smoke density is defined by $naQ = k$, the parameter k being referred to as either the 'extinction coefficient', or the 'coefficient of light absorption'. This is related to the opacity and effective length of light path by the equation:

$$k = \frac{-1}{L} \log_e\left(1 - \frac{N}{100}\right) \tag{18.3}$$

k is expressed in units of metres^{-1} and is thus dimensionally similar to the ratio of filter area to gas volume of spot meters referred to previously. Also if, as seems likely, a and Q are similar for the carbon particles produced under most engine operating conditions, k is linearly related to the gravimetric concentration of carbon in the exhaust.

k thus represents a smoke density parameter independent of the particular design configuration of the opacimeter. It should also be realized that the efffective length L is not necessarily identical to the geometric distance between the light source and the photocell.

Opacimeters may be classified as either sampling, or full-flow, the latter being further subdivided into in-line and end-of-line types. Sampling opacimeters differ from spot meters, of course, in that they can operate more or less continuously, and may thus be used to investigate varying operating conditions. Full-flow meters measure, by definition, the smoke density of the whole of the exhaust emission. In the case of in-line meters the instrument forms a permanent part of the exhaust system either of a test bed or an industrial installation, while end-of-line instruments are of course fitted to the outlet of the system, either permanently, or for an individual test.

The end-of-line meter may be arranged to pass the whole of the exhaust gas through a chamber whose dimensions define the light path, or the light beam may be arranged to pass through the freely emergent smoke plume to the photocell, when the exhaust pipe dimensions determine the value of L.

18.2.3.1 Sampling opacimeters

In its simplest classical form, the exhaust gas sample is extracted from the system by a probe, and passed through a tube having a photocell at one end and a filament bulb at the other. Zero is checked by passing scavenging air through the tube. Not only is this scavenging uncertain in its efficiency, but zero errors occur from soiling of the light source and the photocell. Diffusion of light from both smoke particles and condensation droplets also forms a source of error.

Innovations which provide an acceptable instrument of the sampling type were carried out in the design and development of the Hartridge smokemeter (*Figure 18.3*). Two identical measuring tubes 18 in (456 mm) long are provided, one carrying exhaust gas only, supplied from a sampling probe with pressure control by a relief valve, while the other is continuously scavenged with clean air from a motor-driven fan. The filament lamp and photocell are carried on pivoted arms and can be swung simultaneously from one tube to the other, so that they are only exposed to smoke while a measurement is being made. Even in the measuring position the ventilating air tends to deflect smoke from them. The black interior surface of the tubes, and circumferential fins, minimize the effects of diffusion and reflection.

The instrument has, however, been shown to be adversely affected by pressure pulsations in the sampling line, and if the sample is taken from a point in the exhaust system upstream of the silencer, some damping volume must be introduced into the line[6]. Care must also be exercised if continuous operation is required, to avoid high temperatures near the photocell. It may be necessary to use a cooler in the sample line[9].

Because of the introduction of a variety of volumes in the sampling system, and because the milliammeter has a relatively slow response, rapid changes in smoke level cannot be accurately

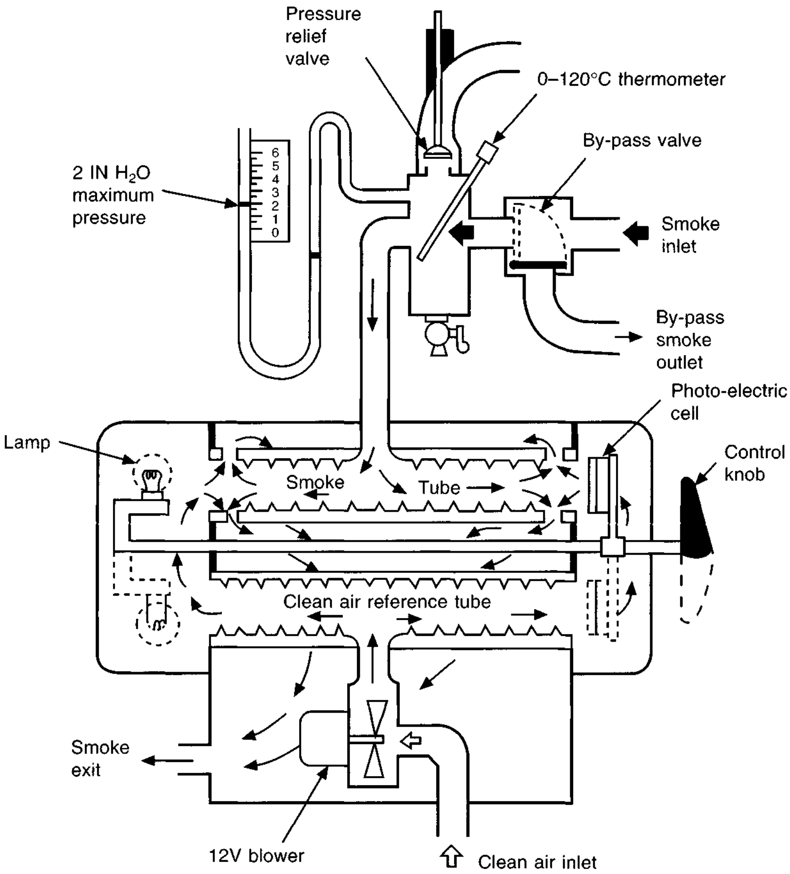

Figure 18.3 Hartridge Smokemeter (diagrammatic)

indicated. Nevertheless, the instrument is still used in Europe for certification testing.

18.2.3.2 Full-flow opacimeters

The full-flow end-of-line opacimeter designed by USPHS for the measurement of smoke emitted by heavy-duty vehicle engines is based logically on the premise that the appearance of the smoke plume discharged from the tail pipe is the essential quality to be assessed. The sensor, as shown in *Figure 18.4,* consisting of the light source and photocell, is carried on a rigid ring which is mounted close above the vertical exhaust pipe, so that the collimated light beam is transmitted diametrically through the plume. By connecting the photocell to suitable indicating or recording instruments rapid response to changing engine conditions can be achieved. A supply of clean air under pressure to the optical system is required both to keep the system cool and avoid soiling by smoke.

The instrument is thus suitable for investigating both steady-state and transient conditions, but suffers from lack of sensitivity on account of the small diameter of smoke plume in which light is absorbed. Also, with smoke other than completely black, changes in ambient light may influence readings. The opacimeter is essentially an instrument for use on engine test bed or chassis dynamometer and an exhaust extraction system is needed; this should not cause distortion of the plume. This distortion can occur with small rates of exhaust discharge, while in the case of large diameter tail pipes turbulence modifies the plume profile, so that there is a limit to the diameter of tail pipe which can be accommodated. Some interference with the plume occurs at 127 mm (5 in) dia., and the instrument is probably not usable with larger pipes[11]. If used in the open air it is clear that the plume must be shielded from wind.

The Celesco Model 107 Smokemeter (*Figure 18.5a*) has been developed as a result of experience with earlier models of generally similar design. Intended for installation in test bed exhaust systems, the detector unit is carried on a length of 150 mm dia. pipe inserted into a vertical part of the system. Protected by a stainless steel radiation shield concentric with the pipe, the light source, detector and collimating devices are carried on a rigid steel ring and are water cooled to prevent thermal drift. Air under pressure is used to ventilate the optical system and to prevent soot deposition. The light source is a light emitting diode (l.e.d.) giving green light peaking at 565 nm and the emission is pulsed at a frequency of 600 Hz.

The photo diode detector is incorporated in a circuit which is tuned and gated to the light source pulse frequency, and is thus rendered insensitive to changes in ambient lighting. The output amplifier (*Figure 18.5b*) also provides digital display of either percentage opacity, or coefficient of light absorption and can simultaneously operate a recorder. Linear correlation with both USPHS and Hartridge instruments has been demonstrated under specific operating conditions.

Such correlation only applies if the instruments are operating with exhaust gas at the same temperature. The effect is not entirely attributable to the functioning of the normal gas laws. At the time of writing, several new models had recently appeared. These are designed to meet the new SAE J1007 (and expected ISO 8178-9) standard, with modern data processing digital electronics. Details on these standards follow below.

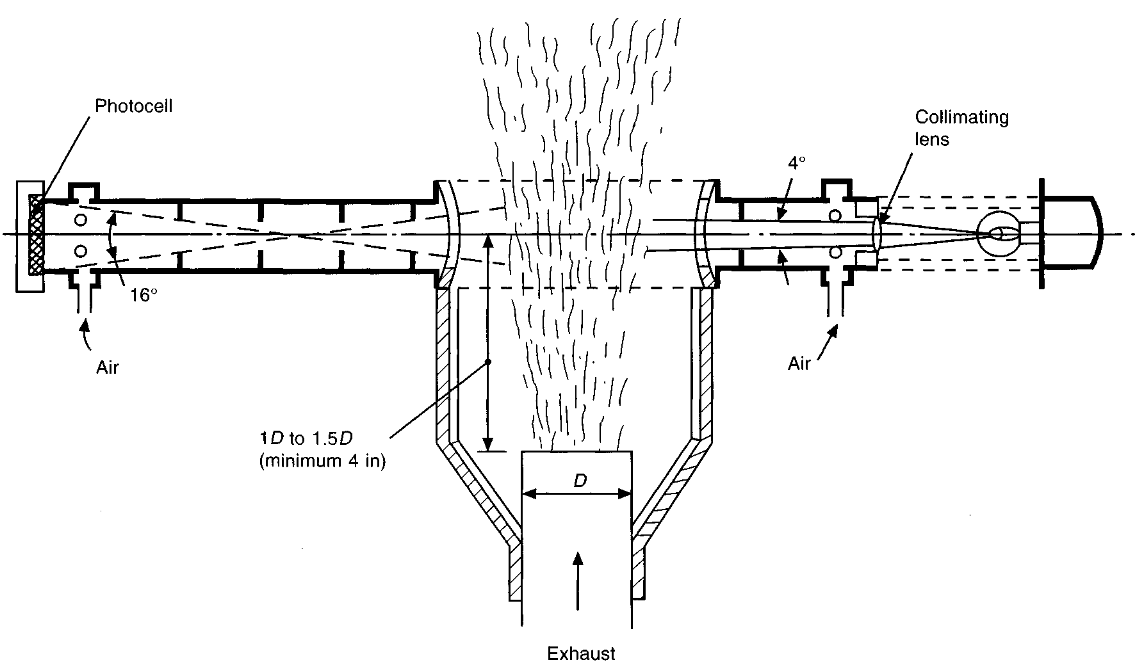

Figure 18.4 USPHS Smokemeter (end-of-line sensor–diagrammatic)

18.3 Calibration and correlation of smokemeters

The linear scale of photocell output of an opacimeter can be checked by inserting neutral density filters of known opacity in the light path. This is subject to a note of caution as regards the spectral distribution of the light source and the spectral response of the detector, as discussed later. Analogously the Bosch evaluating unit, Type EFAW/68, is checked at the 50% opacity point by placing on a stack of clean filter discs a matt black disc pierced with holes reducing its area by half.

The crucial importance of the effective length of the opacimeter light path can be inferred from the curves of *Figure 18.6*. This compares the opacity, calculated in accordance with the Beer-Lambert Law, for meters of different effective length with measurements of the same smoke made on the Hartridge meter (effective length 0.43 m). It will be seen that, at small values of L, a small change in effective length results in a large change in opacity reading, but the instrument is insensitive to smoke density variation. On the other hand, a large effective length gives a high degree of sensitivity to smoke density changes and is insensitive to changes in effective length. The most desirable compromise appears to lie with an opacimeter of about 0.5 m effective length.

Unfortunately, the effective length of the smoke-filled light path of an opacimeter is not subject to determination by absolute standards. Particularly where, as is usual, ventilating air is blown across the faces of the photocell and light source, there is no clearcut termination of the smoke column, some dilution of the smoke in these regions being inevitable. The determination of effective length can therefore be made by passing smoke from an engine simultaneously through the meter and through an opacimeter of known effective length. From the readings of opacity on both instruments the unknown effective length can be calculated using the equation:

$$L = L_o \times \frac{t + 273}{t_o + 273} \times \frac{\log\left(1 - \frac{N}{100}\right)}{\log\left(1 - \frac{N_o}{100}\right)} \qquad (18.4)$$

where

t is the exhaust gas temperature in °C in the smoke measuring zone;

L, N and t refer to the opacimeter under test; L_o, N_o and t_o refer to the known opacimeter.

Alternatively, the value of L may be determined by passing smoke through the opacimeter normally, and then with the ventilating air temporarily cut off, the two values on N recorded again enabling L to be calculated again using eqn (18.4), but where L, N and t refer to the unmodified condition, and L_o, N_o and t_o refer to conditions with the ventilating air cut off.

In either case, the result is subject to the variability of smoke emission from the engine, this introducing an uncontrollable element into the procedure.

When L is known comparability of reading between different opacimeters is secured by scaling the indicating instrument in terms of k in addition to the linear opacity scale. Correlation is only secured, however, by simultaneous operation of the meters on the smoke emission from the same engine. This presupposes also that the gas temperature at the two opacimeters is the same, and this will not be so when an in-line instrument is being compared with an end-of-line one. In fact, the effective path lengths will be inversely proportional to the absolute temperatures.

Alternatively, on the assumption that the smoke is only due to the presence of carbon particles, a determination can be made, under constant engine conditions, of the carbon concentration in gm per cubic metre. A measured volume of gas is passed through an 'absolute' filter which will retain all the carbon suspended in the gas sample. The weight of carbon collected is determined by measuring the increase in weight of the filter. In the case of the Hartridge and Bosch smokemeters the correlation

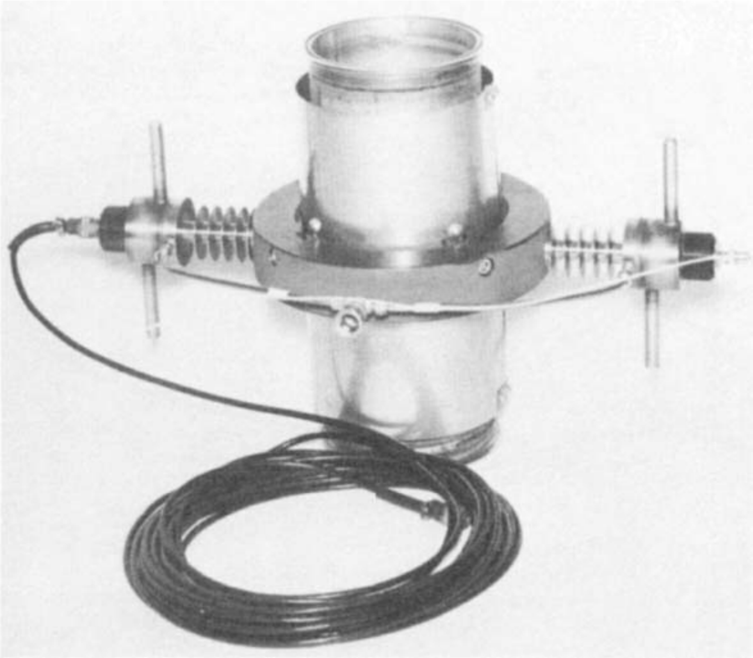

Figure 18.5a Celesco Model 107 Smokemeter (in-line sensor)

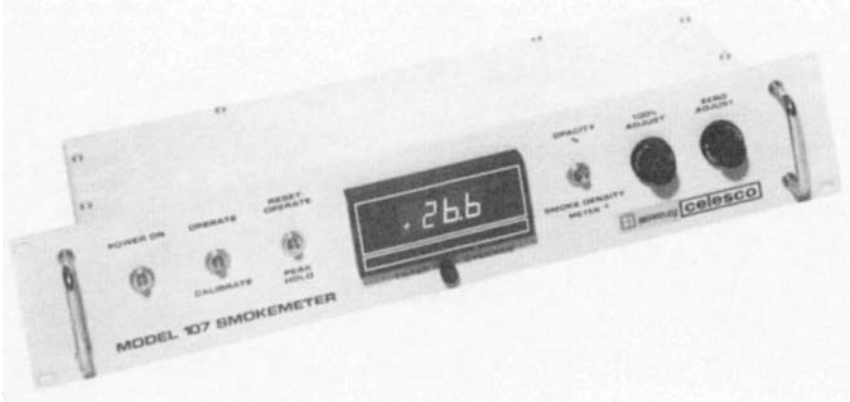

Figure 18.5b Celesco Model 107 Smokemeter output amplifier

has been made in both ways[6] and the results are given in *Table 18.1*. The errors incurred in the carbon concentration measurement are not inconsiderable, and amount to about ± 7 Hartridge Smoke Units (H.Sm.U.).

18.4 Optical system—spectral response

Since a smokemeter is concerned with visibility (or opacity) as appreciated by the human eye, it is clearly desirable that the optical system comprising photocell, detector, and the light source, should have a similar sensitivity to the spectral distribution. This implies maximum sensitivity between 550 and 570 nm, with much reduced response below 430 nm and above 680 nm.

When a tungsten filament light source is used with a wide band detector, the colour temperature must be controlled and a selective filter combined with the photocell. Alternatively, a similar result can be obtained by the use of a light source whose emission characteristics meet the required spectral distribution. There is some evidence that diesel smoke attenuates light of long wavelength (red light) less than light of short wavelength (blue light)[11]. It has also been inferred that as gas temperature falls below about 300°C and coagulation of carbon particles increases, the absorption characteristic of the smoke is shifted reducing the apparent absorption[13].

18.5 Opacimeter specifications

Opacimeter specifications can likewise be classified by their jurisdiction and intended use.

For in-service automotive applications the most important equipment specification is the SAE J1667, published by the US Society of Automotive Engineers. This recommended practice specifies the procedures for a smoke test, and the method of analysis of the results. As a snap acceleration test, J1667 is intended for in-service field use, and is designed for high smoke emitters, not marginal cases. The details of the smokemeter are not specified: it may be full-flow or sampling, with digital or analogue data processing. It is expected that the upcoming ISO standard 8178-9 for off-road vehicular smoke emissions will adopt many of the SAE J1667 provisions.

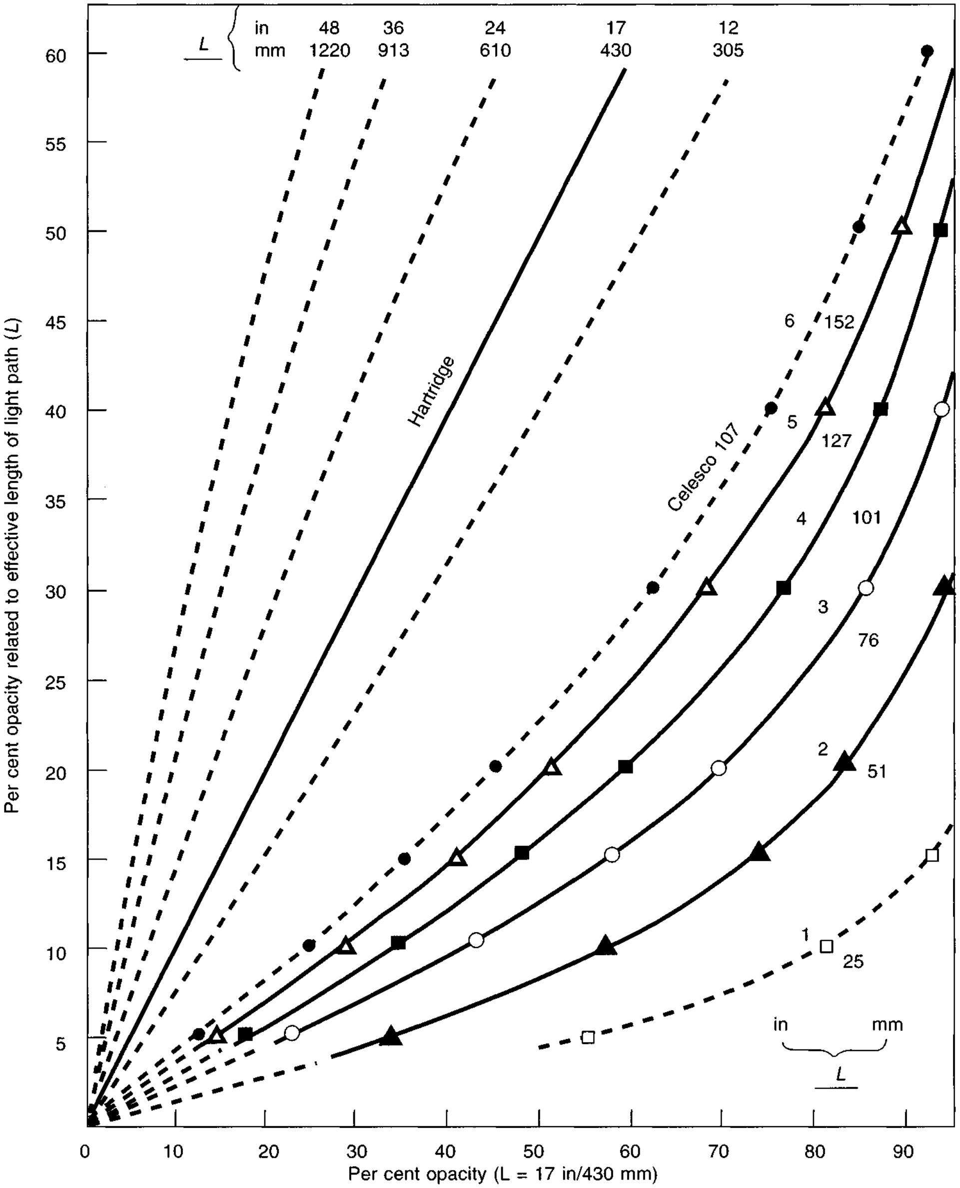

Figure 18.6 Influence of effective length of light path (*L*) on opacity reading

Table 18.1 Approximate correlation of Bosch and Hartridge smokemeters

Hartridge Number	*Carbon (g/m^3)*	*Bosch Number*	*Coeff. of light abs $-k$ (m^{-1})*
10	0.038	1.1	0.26
20	0.100	2.0	0.53
30	0.142	2.8	0.84
40	0.197	3.4	1.19
50	0.265	3.9	1.62
60	0.350	4.4	2.11
70	0.460	4.9	2.81
80	0.620	5.5	3.75
90	0.835	6.2	—
100	—	—	∞

Certification tests typically specify the type of smokemeter to be used. For certification testing in the US the USPHS smokemeter described above is required. In Europe measurements are by an opacimeter such as the Hartridge described above. Both opacimeters and filtering smokemeters are acceptable for certification testing in Japan.

Figure 18.7 illustrates the differences between the typical European sampling opacimeter (Hartridge) and the American full-flow, end-of-line instrument required by Federal Regulations (USPHS opacimeter). *Figure 18.8* shows the set up for a typical use of the Hartridge.

18.6 Visibility criterion—public objection

In the case of road vehicles, the basis of public objection to the diesel engine is the degree of visibility of the exhaust smoke.

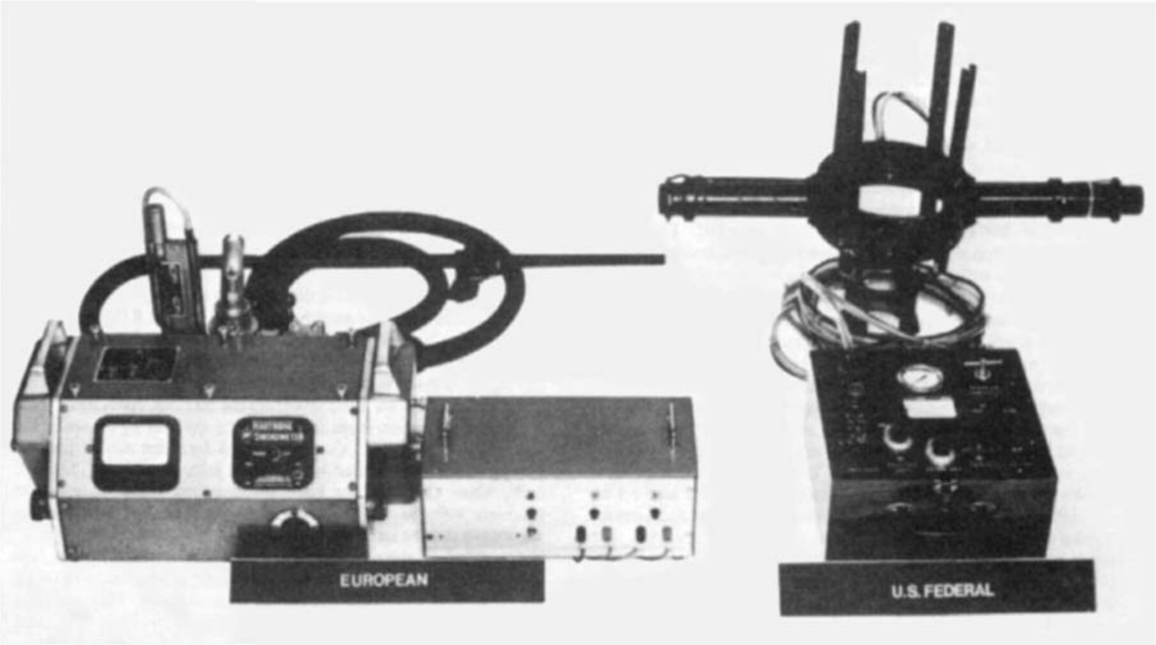

Figure 18.7 Typical European (Hartridge) and US Federal (USPHS) opacimeters

To meet the need for a quantitative (numerical) criterion of such objection, the Motor Industry Research Association (MIRA) and the Warren Spring Laboratory of the UK Department of Trade and Industry carried out tests in which a wide variety of vehicles were driven under full-load constant-speed conditions past neutral juries of people who were required to register whether they considered the smoke emitted as 'acceptable' or 'not acceptable'[18].

The smoke density (opacity) was measured at the same time with Hartridge smokemeters carried in the vehicles. A simple relationship between smoke density, size and speed of the engine, and acceptability, emerged. This is given by the formula:

$$C\sqrt{G} = K \qquad (18.5)$$

where

C is the carbon concentration (gm/m^3);

G is the nominal rate of gas emission (engine displacement rate in litres/sec), and

K is a constant whose value depends on the degree of visual acceptance.

For $K = 3$, 75% of viewers found the smoke unacceptable, for $K = 2$, 50%, and for $K = 1.5$, 25% of viewers found the smoke unacceptable.

A similar series of tests was carried out by a committee of the British Standards Institution in drawing up an automobile smoke standard[19] with similar results. Furthermore, MIRA and the Warren Spring Laboratory repeated their tests more recently with more up-to-date vehicles, with the same type of relationship resulting, although the index for the 'G' term differed slightly[20].

18.7 Test methods and procedures

In the case of stationary plant it is sufficient to measure smoke emission at the rated speed at both full rated load and at any permitted overload. This could be done either on the manufacturer's test bed before delivery, or on site as finally installed, and, subject to atmospheric conditions, identical results should be obtained.

For vehicle engines the problem is more complex. Manufacturers need to establish a procedure ensuring repeatable and consistent results while covering the normal performance test. This is most easily accomplished on an engine dynamometer test by measuring steady-state full-throttle behaviour (torque, power, fuel consumption and exhaust smoke opacity) at a sufficient number of individual speeds covering the operational range, i.e. from maximum governed speed to a speed below that giving maximum torque. In order to confirm that vehicles in service conform to environmental requirements such a procedure is clearly impracticable, even if such expensive equipment as chassis dynamometers could be made available. Legislators require a much quicker and simpler surveillance test.

Such a simple test, originally devised by the Belgian authorities, is the so-called 'free acceleration test' 'snap acceleration test' or 'Snap idle test', carried out on the stationary vehicle with disengaged transmission. With the engine fully warmed up and idling, the smokemeter (in Europe usually the Hartridge or UTAC instrument) is connected to the vehicle exhaust tailpipe and the throttle pedal is rapidly moved to the fully open position, remaining there until maximum governed speed is reached, usually in between 1 and $1\frac{1}{2}$ s and held for a few seconds.

The maximum smoke reading reached during the operation is noted and the engine returned to the idling condition, remaining there until the original idling state is restored. The whole procedure is then repeated until three successive smoke readings are found to lie within ± 2% opacity. The average of these is taken as the representative value of the smoke emission.

It is clear that this procedure bears little or no resemblance to any normal vehicle engine operation, and many doubts as to its technical value have been expressed, especially as the European opacimeters used with it are fundamentally incapable of the necessary speed of response required by the transient nature of the test. Investigations by MIRA and others[10,21,22] demonstrated that the smoke values obtained from free acceleration tests on various engines gave no correlation with maximum smoke readings obtained from steady-state power curve tests carried out on the same engines. Neither did the free acceleration smoke

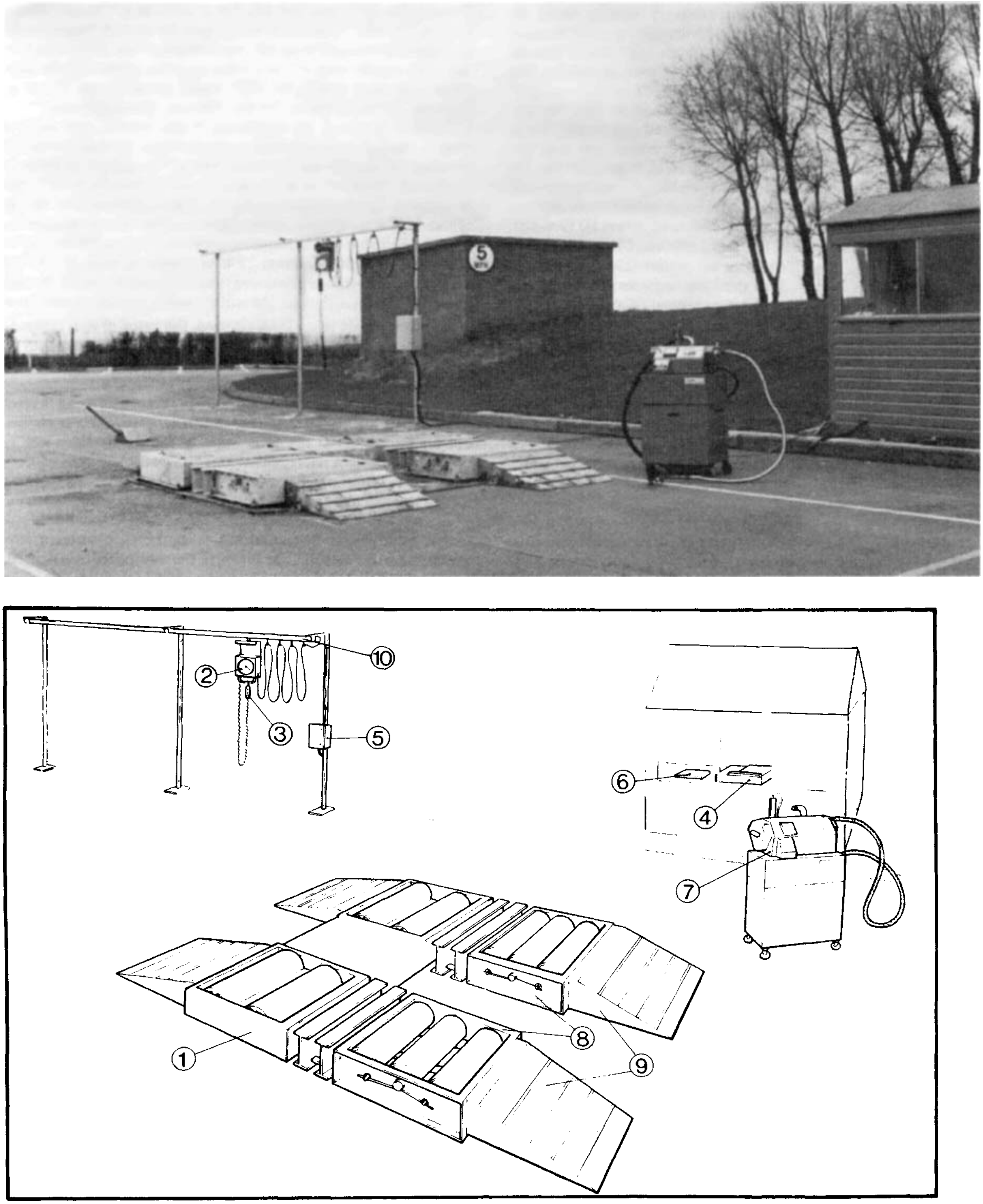

Figure 18.8 Equipment layout for British 'Lug-Down' test

1 Lug-down rolls
2 Driver's aid tachometer
3 Handset
4 Plotter
5 Switch
6 Test record pad
7 Hartridge Mk III smokemeter and power pack
8 Bogie rolls
9 Ramps
10 Stand

readings made on one type of smokemeter correlate with those obtained on another type. However, a snap acceleration test has been accepted by the SAE, and is expected to be adopted by ISO (details of these appear above). These tests are designed to catch gross emitters in need of maintenance, and are fast, cheap, and easy to perform.

For certification testing in the US, the USPHS smokemeter described above is required. The test procedure is the US Federal Smoke Test, which consists of a six step cycle that is designed to produce the most severe smoking conditions. The test is performed on an engine test stand, and is repeated three times.

The ECE R24 cycle is used for certification testing in Europe. The engine is run on a test stand at steady state, at full load at six defined speeds between 45% and 100% of its rated speed. Smoke measurements are by an opacimeter such as the Hartridge described above.

The smoke certification for Japan and Korea is similar to the European R24 test, but consists of only three speed steps (40%, 60% and 100% of rated speed). Opacimeters or filtering smokemeters are acceptable.
Reference: *Diesel Fuel Injection,* Robert Bosch GmbH, 1994.

18.8 Typical smoke regulations

18.8.1 Road vehicle applications

The regulated level of smoke limits has not moved lower in recent years with either the severity or frequency of the limits for gaseous and particulate emissions. This may reflect the fact that as particulate limits continue to be reduced, smoke emissions are simultaneously curbed too. A vehicle cannot hope to meet particulates limits if it suffers from high smoke emissions.

For on-highway vehicles in the US Federal Smoke Test, opacity limits in the acceleration and lugging phases are 20% and 15% respectively. The peak opacity may not exceed 50% (this limit will fall to 35% after 2001). In Europe the maximum permissible absorption coefficient is defined by a curve which is a function of the nominal exhaust gas flow rate; higher flow rates must achieve lower smoke levels. The maximum smoke level over the Japanese 3-step smoke test is 40% opacity, lowering to 25% opacity around 2005.
(Reference: *Diesel Fuel Injection,* Robert Bosch GmbH, 1994).

18.8.2 Regulations other than for road vehicles

In the USA, off-highway vehicles are subject to the same standards as the on-highway ones. Europe and Japan might follow ISO 8178-9 on smoke when that standard is finalized, as these countries have already adopted other ISO 8178 provisions for gaseous and particulate emissions.

18.9 Conclusions—future legislation

Smokemeter technology continues to advance, with consequent improvements in the resolution and repeatability of the measurement. Smoke regulations are among the most well-harmonized: between nations around the world, and between on-road and off-road applications. However, as particulate emission limits continue to be reduced, smoke limits are becoming somewhat—though not completely—academic. The USA and Japan are both proposing lower smoke limits in the future.

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