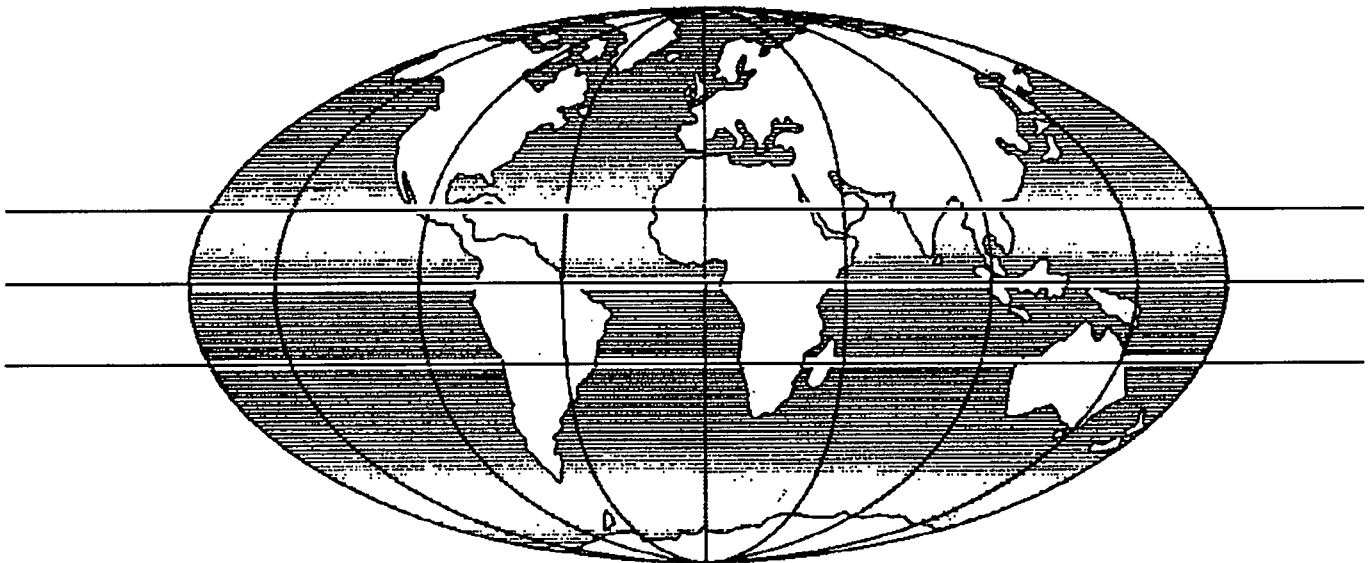




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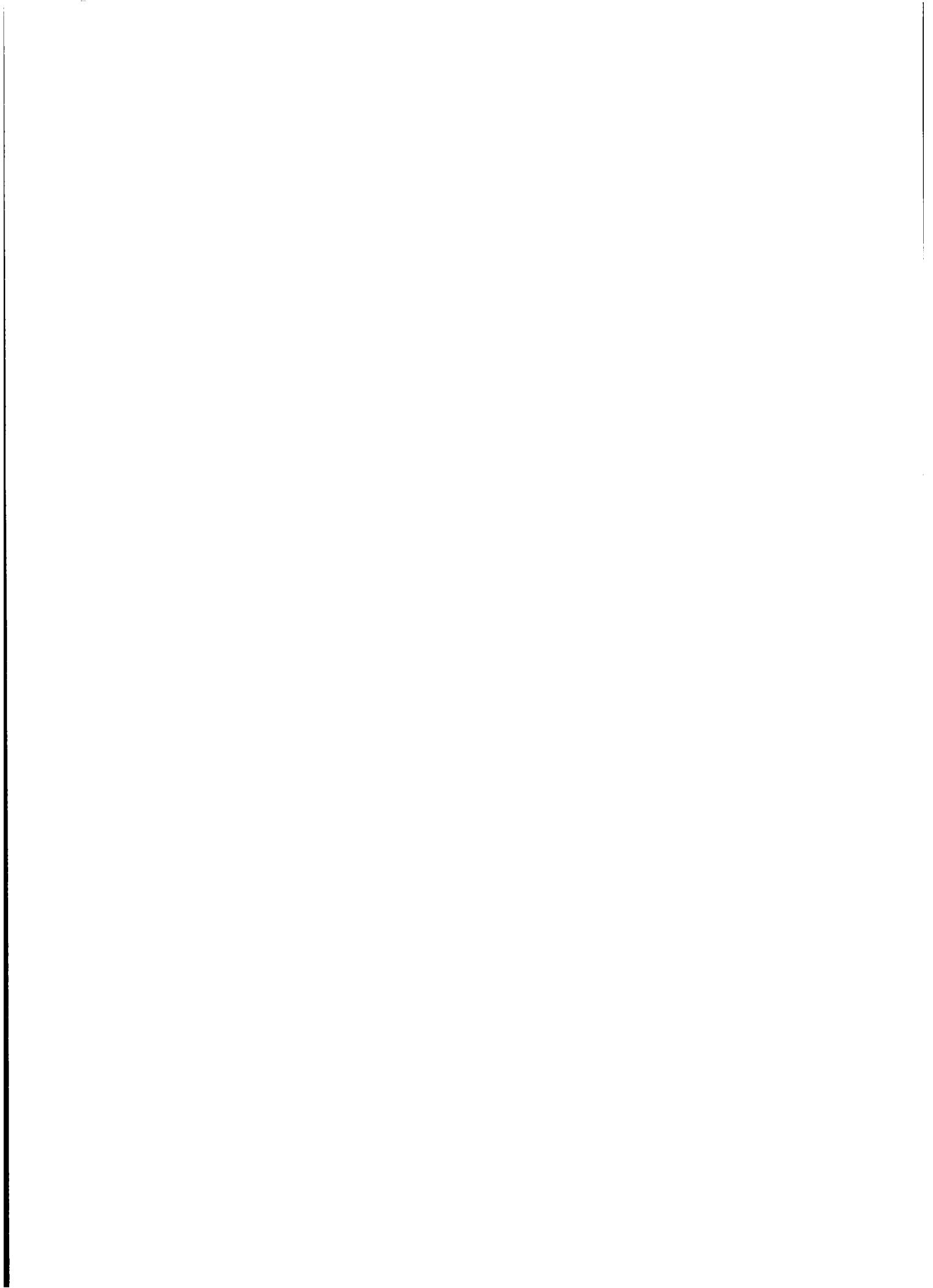


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**BLACK SMOKE EMISSIONS
AND
FUEL CONSUMPTION**

by
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1 INTRODUCTION

The emission of black smoke by diesel fuelled trucks and buses is an everyday sight in many countries in the world. At best, it represents an unpleasant smell and more dirt to cover ourselves and surroundings; at worst it can present a health hazard through the inhalation of minute particles coated in hydrocarbons and is always a sign that the vehicle is operating inefficiently and wasting fuel.

Many operators are reluctant to perform extra work on their vehicles during maintenance periods and will not do so unless it can be proved that they will save money. In addition, while there are no routine or random smoke checks in many countries, there are no external incentives to improve this particular aspect of a vehicle's performance.

The Overseas Centre of the Transport Research Laboratory in the UK has been carrying out research into the problems of black smoke for some years now and has recently carried out a joint project, with the Central Institute for Road Transport in Pune, to measure black smoke emissions from two fleets of vehicles and to correlate the emissions with the fuel consumed by the same vehicles. The aims of the project were firstly, to demonstrate to operators that cleaning up the exhausts of their vehicles will save them money through reduced fuel costs and secondly to discover whether black smoke emissions in India were inherently high because of fuel quality or engine design.

2 THE CAUSES OF BLACK SMOKE

Both petrol and diesel fuelled vehicles burn their fuel by mixing it with air within the cylinders of the engine. In a petrol engine the proportions of air and petrol are restricted to a very small range, normally around the perfect, or stoichiometric, ratio of 14.7:1. This is quite different in a diesel fuelled engine. For this method of combustion, the amount of air drawn in is almost constant and the power output is determined by the amount of fuel injected.

Theoretically, except when starting from cold, there is always more than sufficient air drawn into a diesel engine to ensure complete combustion of the fuel. This should result in very low levels of unburnt hydrocarbons, carbon monoxide or black smoke being emitted. When starting from cold a quantity of excess fuel is injected and hence the higher levels of smoke and other pollutants emitted.

As the amount of fuel injected has to be carefully metered for efficient combustion it follows that the fuel injection system must not only be constructed to high precision but also be well maintained and correctly adjusted. If too much fuel is injected or insufficient air drawn in at any time it is apparent that not all of the fuel will be fully burnt and, consequently, particles of carbon that have not been fully converted into CO₂ and unburnt hydrocarbons will be emitted. Although carbon in itself is not particularly toxic it is possible for the very finest of particles to penetrate into the human lungs. Unburnt hydrocarbons, particularly those known as Polycyclic Aromatic Hydrocarbons [PAH] are known to contain carcinogenic compounds such as

benzo[a]pyrene and can adhere to the surface of these particles.

Other causes of black smoke are:

- Poor design of engine and associated injection system
- Wear in the system
- Dirty filters or injectors
- Tampering with or deliberate mal-adjustment of injection system
- Overloading of vehicle
- Poor fuel quality [including adulterated fuel]
- Binding of brakes

In many countries the problems of black smoke and other pollutants from diesel vehicles have been studied for some considerable number of years and this is not the place to discuss the full extent of the problem. There are advanced technological methods for controlling the emission of these pollutants including particulate traps, exhaust catalysts and electronic control of the fuel injection. These methods all expect a starting point of an engine that is well maintained and adjusted and it is to this point that all diesel vehicles should be brought.

Although the absolute number of vehicles in most developing countries is not high, most are commercial vehicles powered by diesel engines. The traffic density along main roads may be as high as in any country and when coupled with high emissions and a large number of the poorest sections of the community living and working near the roadside it can be seen that the problem is extremely severe and requires urgent attention. It can be difficult to persuade operators to spend money on repairing or maintaining their trucks if they can see no financial benefit and there is often no legislation or enforcement to control black smoke emissions. This research is intended to demonstrate to operators that, by maintaining their vehicles so that black smoke is minimised, they can save money by reducing fuel consumption.

3 THE MEASUREMENT OF BLACK SMOKE

3.1 Methodology

There are two ways of obtaining black smoke emissions from a vehicle under test. The most complex is to mount the vehicle on a dynamometer or rolling road, and, by altering the resistance to the driving wheels, the vehicle may be driven at a variety of speeds and loads to determine its emissions of black smoke. The second way, and by far the easiest, is the Free Acceleration Smoke Test. In this test the vehicle's engine is run until normal operating temperature is achieved. Then the accelerator pedal is pressed down to its maximum extent and kept there until the engine reaches its governed speed. By this action the engine is accelerated at the maximum possible rate against its own inertia and hence is operating at full power [and fuel delivery] through its operating speed range. The peak smoke level is then detected and recorded. This is repeated several times in order to obtain a mean reading of peak smoke level. The test is defined precisely in ECE Regulation 24 [Intereurope 1980] and is used in the United Kingdom for regular in-service inspections [the MOT test]. This is the method used in this project to measure black smoke.

In order to measure the concentration of smoke a device called an opacimeter is used. This has supplanted the older, filter type devices and measures the density of smoke by shining a beam of light across the exhaust plume and detecting the attenuation in light strength. Meters can be obtained that sample either the entire plume or part of it and it is the latter type that are commonly used today. The meter electronics detect and record the peak smoke level measured during each acceleration and can determine whether a test has been carried out correctly. A smoke test has recently become compulsory during the annual in-service inspection in the UK and a number of meters have been approved to comply with the requirements of the UK's Vehicle Inspectorate [Vehicle Inspectorate, 1992]. These meters operate either from mains electricity supply or from rechargeable batteries and can therefore be used wherever required. For the purposes of this experiment, a Sun ASA 200 Advanced Smoke Analyser was used. The opacity of smoke is indicated in units of the Smoke Absorption Coefficient [$k \text{ m}^{-1}$].

3.2 Equipment Description

The ASA 200 meter is a compact unit that is easily transported in a large briefcase or, when in use, the essential parts can be carried around a depot or workshop reducing the possibility of damage by being left on the workshop floor.

The smoke meter uses a modulated light emitting diode [LED] as a light source and a solid state photodiode light receiver and is controlled by a computer within the handset. The computer measures the light level received at the photodiode when attenuated by the exhaust smoke passing through the meter, calculates the density of smoke, records the peak level seen. The computer then determines, on the basis of the test results so far, whether any more tests are required and whether the vehicle is a PASS or FAIL [this is based on the UK standard for normally aspirated [$k=3.2$] or turbo-charged vehicles [$k = 3.7$]].

The smoke is sampled by a sensor unit inserted into the vehicle exhaust, linked, via a cable that carries power and data, to a handset. The sensor unit contains the light source and receiver, a fan for providing a curtain of clean air across the optics and a clamp for fixing the unit to the exhaust tail pipe. The handset can be disconnected from the sensor and plugged into its base station which provides battery charging and a link to the printer for output of results. The printer is also battery powered and equipped with its own charger. Verification filters are also provided to enable calibration of the meter to be carried out at zero [$k = 0$] and a mid point value [approximately $k = 1.7$].

The operation of the meter is controlled by the in-built computer that displays commands and options on the handset LCD display screen. A zero check is performed at the beginning and end of each test to ensure that the optics are not excessively dirty and to enable a correction to be made if not absolutely clean. When the test is started the handset issues commands from the display to start accelerating, to release the throttle and when to start and stop the engine. It also displays the individual peak smoke readings and the final result.

The UK regulations permit the number of accelerations to vary between 4 and 10, a very clean

vehicle may therefore pass within 4 accelerations while a dirtier vehicle is given up to 10 attempts to reach the limit. In all cases the result is obtained by taking the mean of the last four values and subtracting the zero check reading. On completion of the test the handset is connected to the printer and full results are output. The entire test takes considerably less than five minutes once the vehicle's engine has reached operating temperature.

4 VEHICLES TESTED

25 buses from PMT were selected ranging in age from new to 25 years old and manufactured by both Tata and Ashoke Leyland. From GPT, 25 Tata trucks ranging from one to 15 years old were selected and two new luxury Tata coaches. The vehicles were tested, approximately once a week for several months, immediately on return to their depots for servicing. If work was carried out on their engines they were tested again before going back on the road. At the same time, fuel consumption data for the comparable period was collected, supplemented in the case of GPT by an Index of Performance which takes into account the load factor and route difficulty of their trucks. It should be noted that fuel consumption data is recorded only from records of fuel put into a vehicle's tank.

5 DATA ANALYSIS AND DISCUSSION

5.1 Correlation of black smoke with fuel consumption

At the beginning of the project it was hoped that times series data for the vehicles could be plotted that would demonstrate the link between black smoke and fuel consumption. A total of almost 500 valid data points were obtained during the course of the project, an average of nearly 10 per vehicle. The scatter in smoke data when compared to fuel consumption data, especially when the complete sample population was studied [Table 1], meant that it did not prove feasible to combine individual sample points for the vehicle fleets as a whole. Individual vehicles in some instances did show the expected, positive correlation between black smoke and fuel consumption over time, however the scatter in smoke levels, in particular for the PMT buses, was such that no meaningful conclusions could be drawn.

Table 1. Summary statistics for data collected

		All Vehicles	GPT Vehicles	PMT Vehicles
Smoke [k m⁻¹]	Mean	2.51	3.68	2.12
	Std Dev	1.60	0.45	1.76
Fuel Consumption [L/100 km]	Mean	28.30	27.54	29.23
	Std Dev	3.10	3.24	2.72

Some of the vehicles, especially the buses, registered extremely high smoke levels during their first few accelerations and this did cause some dirtying of the optics. It proved necessary to ensure that the optics were cleaned before each test of these dirtier vehicles. This proved to be the only problem that affected data collection during the experiment and showed that the use of this type of sophisticated equipment in the field, even with temperatures over 40°C, was eminently practical.

Given a subjective view of the high levels of black smoke, from diesel vehicles in India, the mean smoke levels recorded appear to be quite low although individual vehicles sometimes registered smoke levels that were beyond the range of the smoke meter [$k > 9.99 \text{ m}^{-1}$]. Figures 1 and 2 show the distribution of individual peak smoke levels for each sampled vehicle in the two fleets. Section 5.2 discusses the overall smoke levels measured.

Figure 1 Distribution of peak smoke for GPT vehicles

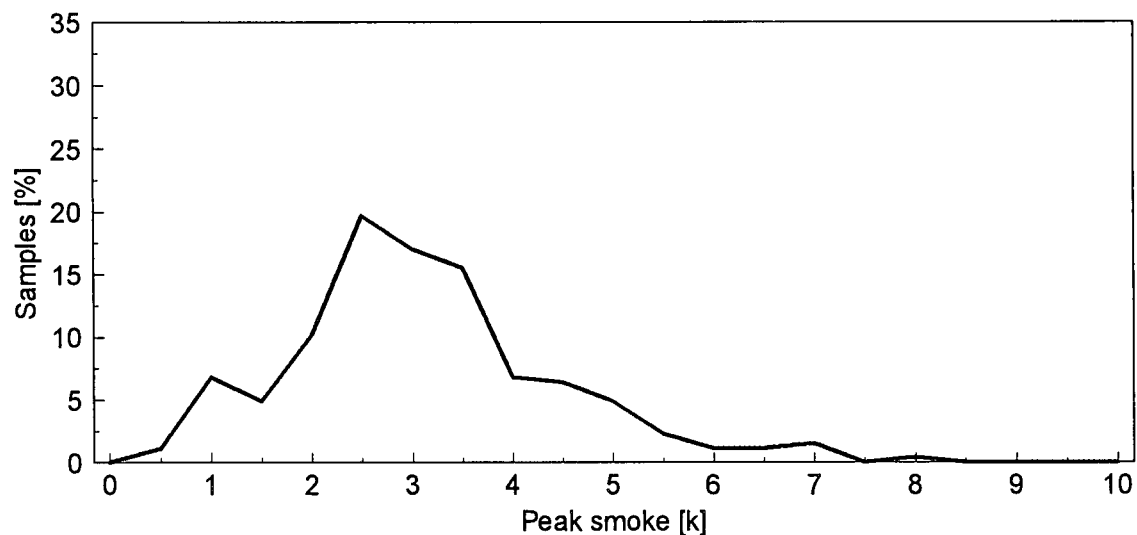
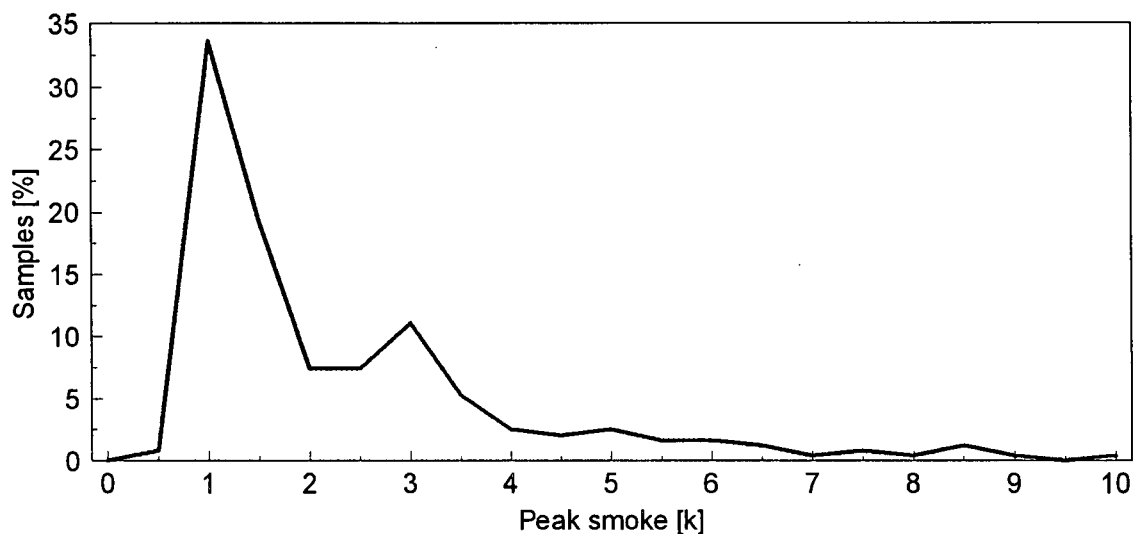
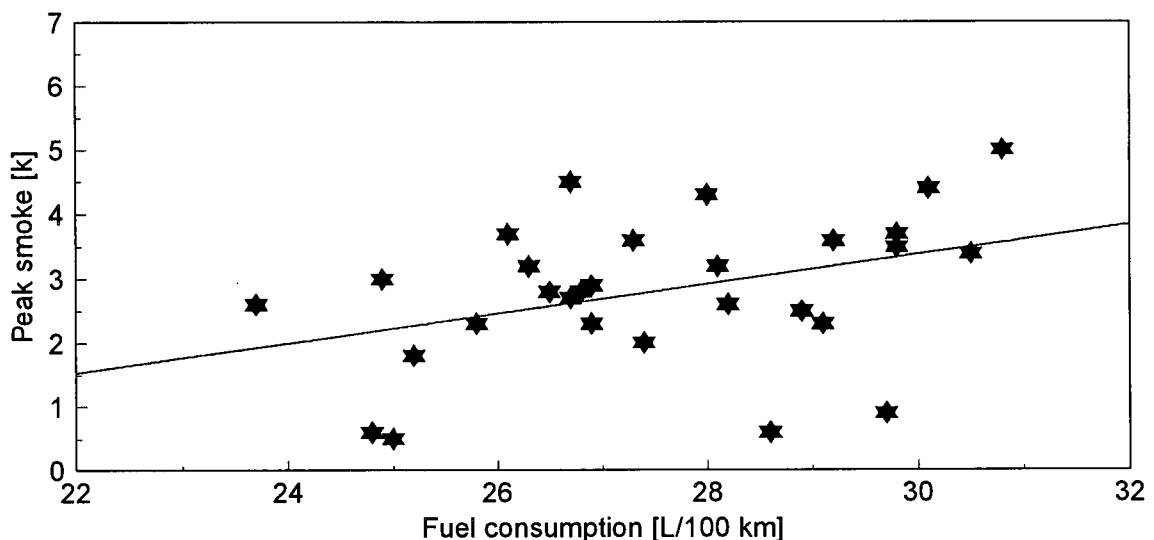


Figure 2 Distribution of peak smoke for PMT vehicles



In addition no correlation between age of vehicle and smoke was established. It may be that the vehicle fleets selected were atypical of Indian commercial vehicles but it cannot be proven from this sample. Certainly it is true that both fleets of vehicles underwent regular preventative and curative maintenance. It was decided to remove the time/distance element from the analysis and concentrate on correlating black smoke with fuel consumption using the mean figures for each vehicle and by this method a much clearer picture emerges. For each fleet of vehicles there is a distinct positive relationship between black smoke and fuel consumption as shown in figures 3 and 4. These figures illustrate the effect that an increase in black smoke has on fuel consumption and figure 3 shows that for each 0.1 increase in 'k' value the fuel consumption increases by almost 0.5 L/100 km. For an increase from $k = 2$ to $k = 4$ the fuel consumption will increase from 23.9 L/100 km to 32.6 L/100 km [this is the equivalent of an increase from 4.2 km/L to 3.1 km/L].

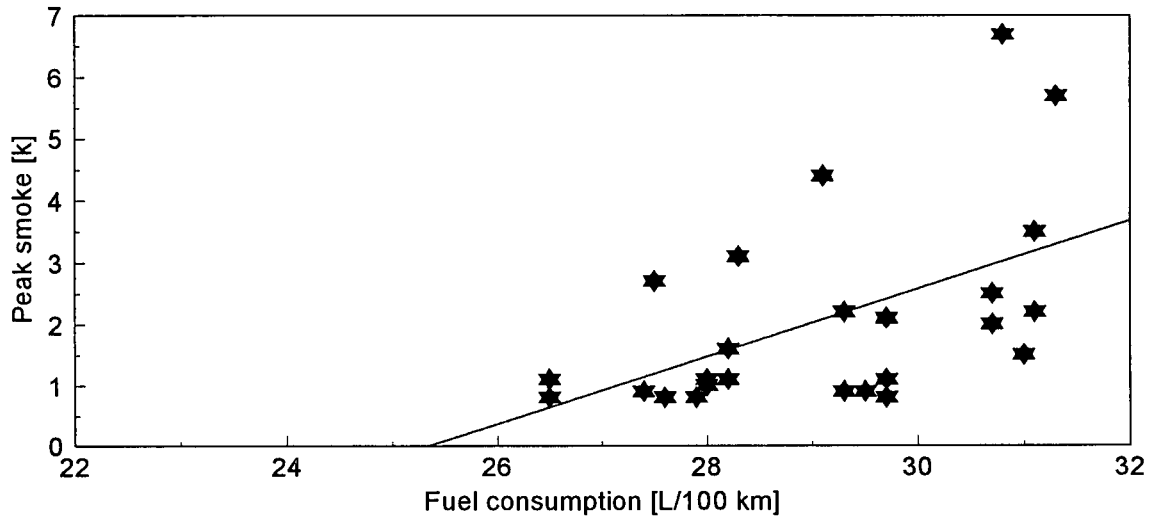
Figure 3 Variation of mean peak smoke with fuel consumption for GPT vehicles



Similarly, figure 4 shows that an increase in black smoke for city buses from $k = 2$ to $k = 4$ would result in an increase in fuel consumption from 29.1 to 32.7 L/100 km [this is the equivalent of an increase from 3.4 km/L to 3.1 km/L]. It is apparent from this that the effect on fuel consumption, even when using rough and ready ways of measuring fuel consumption, can be estimated from the levels of black smoke during a free acceleration test.

Truck and bus operators are, of course, really only interested in their profitability; how do the results from this research affect them? To put this in financial terms it can be calculated that improving the peak smoke emissions from $k = 4$ to $k = 2$ can save between 2000 and 5000 litres of fuel per vehicle per year for a typical annual distance of 60000 km. Calculations for the extra costs involved in maintaining vehicles to a higher standard are not difficult to make and the benefits in terms of fuel saved are considerable. In national terms, the cost in lost productivity caused by ill health from pollution should also be included when considering a national programme of enforcement or incentives to reduce black smoke from diesel vehicles.

Figure 4 Variation of mean peak smoke with fuel consumption for PMT vehicles

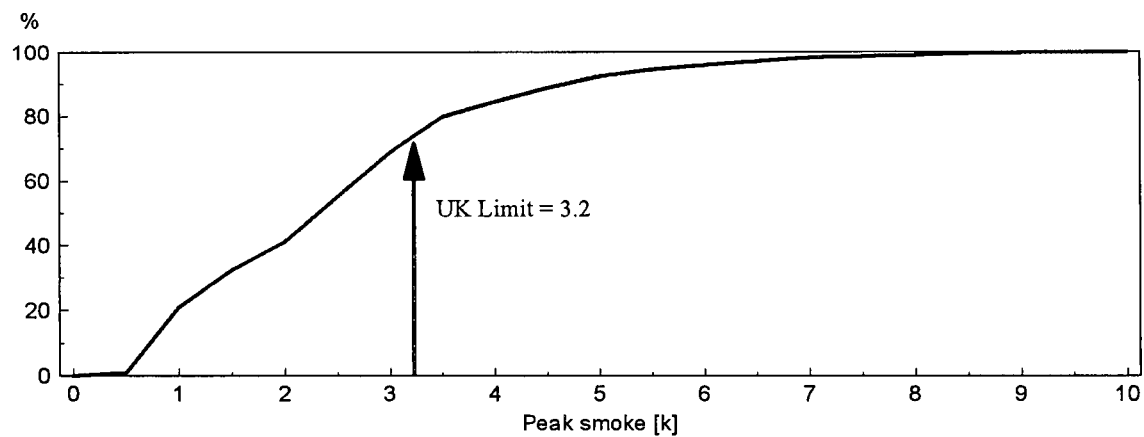


5.2 Overall black smoke data

Table 1, above, shows that the overall mean peak smoke value was $k = 2.51 \text{ m}^{-1}$. The limit in the UK for vehicles tested during their annual inspection is $k = 3.2 \text{ m}^{-1}$ for normally aspirated vehicles with a slightly higher limit for turbo-charged vehicles. As all the vehicles sampled during this project were normally aspirated the lower figure is used for this comparison. Figure 5, below, shows the cumulative distribution of all the data collected during the sample. It is very interesting to see that nearly three quarters of all the tests carried out gave results that meant the vehicles would have passed the UK standards. This enables two major conclusions to be drawn:

- That vehicles in good condition produce little smoke
- That the fuel available to these two fleets of vehicles is of a quality such that excessive black smoke is not generated

Figure 5 Cumulative distribution of all peak smoke data



One only has to travel on roads in many countries to realise that this happy state of affairs is not universal. The ability of different fleets of vehicles to meet such standards as the UK Vehicle Inspectorate sets does show what is possible without the use of very modern vehicles or indeed very high technology. The high technology utilised in the smoke meter enables the an accurate, complex piece of equipment to be used reliably in adverse conditions both for assistance in maintenance and in enforcement situations.

6 CONCLUSIONS

- 6.1 The use of advanced smoke test equipment in adverse conditions of high temperatures and humidity was achieved, reliably and without significant problems.
- 6.2 Positive correlations between peak black smoke, when measured by the free acceleration smoke test, and fuel consumption were derived from measurements taken during a six month period from two fleets of vehicles.
- 6.3 The potential for the introduction of incentives to improve black smoke emissions has been demonstrated in terms of possible fuel savings.
- 6.4 Nearly three quarters of the peak smoke tests performed would have passed the UK test standard. The vehicles from both fleets sampled were maintained to a good standard.
- 6.5 The standard diesel fuel available to the fleets under test is of good quality and does not cause excessive smoke.

ACKNOWLEDGEMENTS

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