Annex 3

The regulatory test method, in-service emissions testing, the measurement of exhaust particles and particles research

A3.1 Limitations of the regulatory test method

1. Ntziachristos *et al*. (2004a) have noted that there are clear advantages to the CVS procedure for certification tests. Dilution of the exhaust reduces the risk of water condensation in the sampling and transport lines; stabilisation of the exhaust reduces pressure and temperature fluctuations, thus simplifying the sampling procedure; and flow rate is precisely controlled and measured. However, a method based on the use of a CVS and the measurement of filter mass alone – whether for comparison against a standard or for any other purpose – has several limitations. Some of these limitations are outlined below.

- Reliability of measurements for low-emitting vehicles. A significant problem with the filter technique is the very low mass emissions associated with modern vehicles.
- Lack of control over sampling conditions. Several exhaust sampling parameters are left uncontrolled in the CVS.
- The particle size distribution and other metrics are not determined. A standard based solely on total particulate mass is probably not ideal in terms of minimising the risks of exhaust emissions to health.
- The single mass value does not permit a detailed understanding of factors influencing particle emissions.

2. Consequently, various alternative methods have been explored for sampling and characterising exhaust particles, and a number of metrics have been proposed in addition to filter mass. Possible metrics for particle characterisation include the size distribution (number or mass-weighted), number concentration, surface area and information on the chemical character of particles (Ntziachristos and Samaras, 2003). However, there are a number of issues relating to both the nature and measurement of particles that still need to be resolved.

A3.2 In-service emissions testing

3. For legislative purposes, the Type Approval testing for particulate emissions is only applicable to diesel engines. At the Type Approval stage, particulate emissions have conventionally been measured gravimetrically. However, EU Directive 99/96/EC introduced the European Load Response (ELR) test, applicable to Euro III and subsequent engines. This engine test consists of a sequence of load steps at constant engine speeds and was introduced for the purpose of smoke opacity

[1] Full details of the FAS test method and associated equipment are available at http://www.gea.co.uk/docs/130.doc.

measurement. It is important to note that when these vehicles enter service, yearly MOT testing is undertaken using only a measure of exhaust opacity, through the use of an opacity meter[1]. The actual test procedure is referred to as the Free Acceleration Smoke (FAS) test and involves a sequence of up to six accelerations, leaving a gap of at least 10 s between each full depression of the throttle, from engine idle to engine cut-off (governed) speed. However, some subjectivity is also applied to this test procedure, as the results can be affected by the way in which the throttle is depressed and released. Furthermore, it is essential to ensure that the engine and any turbocharger fitted should be at idle prior to the start of each FAS cycle. The calculated smoke value is the arithmetic mean of the last three measurements, on the basis that no measurement is less than 75% of this mean smoke level. In the event that this criterion is not met, the test is returned as void, forcing a repeat or ultimately a test failure.

A3.3 Issues relating to the measurement of exhaust particles

4 Kittelson *et al*. (2002) have noted that the particle size distribution in diesel exhaust is influenced by many factors. These include engine condition, fuel and lubricating oil composition, exhaust system configuration, the sampling system used and the sampling conditions. Engine and sampling system stabilisation as well as previous engine operating history play important roles in determining the size distribution. Furthermore, ambient weather conditions, such as temperature, also affect on-road size distributions. All of these factors make precise definition and simulation of the on-road operating and dilution conditions very difficult. Measurement of the nucleation mode is the most difficult because it is dominated by particles that are formed by the condensation of lower volatility organic precursors as the exhaust dilutes and cools; this process is extremely dependent upon dilution conditions and these nuclei and their precursors may be strongly influenced by losses and sampling artefacts. Ntziachristos *et al*. (2004a) noted that various results could be reported depending upon the sampling parameters used in a particular study.

5 Once the exhaust gas has left the exhaust pipe, several phenomena may occur in the dilution tunnel and sampling system, and these are responsible for changes in a range of properties associated with the PM. They may lead to errors in the particle mass measurement, but more significantly to the characterisation of particle number emissions and size distribution (Burtscher and Majewski, 2004). They include the following.

- Condensation/nucleation: this process occurs in the exhaust system and sampling lines and can be influenced by the way in which the exhaust is diluted and cooled.
- Particle coagulation: the coagulation rate depends on the square of the number concentration. It affects both particle number and size distribution.
- Particle sample losses: although sampling systems are designed to limit these losses, they may occur through several processes including inertial impaction, diffusion and thermophoresis[2] and electrostatic deposition. The loss of

[2] Thermophoresis is the induced movement of PM by thermal gradient effects. Transparent particles tend to move towards heat sources while opaque particles move away from heat sources.

particles in the smallest size fractions, due to their high diffusion coefficients, is disproportionately high.

- Deposition/re-entrainment: particles may be deposited and subsequently re-entrained in the exhaust system.

- Particle generation from sampling system: particles may be also generated from within the sample lines used to convey the gas from the exhaust pipe to the dilution tunnel.

A3.4 Particle research programmes

6. A novel PM sampling system was designed and constructed in the EU Fifth Framework PARTICULATES project. To address the concerns relating to particle sampling conditions and to allow preferential conditioning of aerosol samples, Ntziachristos *et al*. (2004a) designed a partial-flow sampling system that drew exhaust directly from the tailpipe. The intention was not to develop a system for use in certification tests, but rather to achieve the repeatable formation of the nucleation mode in the laboratory using specific sampling parameters (dilution ratio, residence time, temperature and humidity). This would allow the identification of cases (engine operating modes, fuels and so on) where there is a potential for nucleation mode formation. The sampling system was also designed to measure a broad range of particle properties over transient tests, including size, number concentration and surface area. Additionally, the physical separation of solid soot particles and volatile particles was deemed necessary.

7. The GRPE-PMP programme was initiated in January 2001 and conducted under the auspices of the UNECE WP29/GRPE group. The countries that participated actively in the PMP project were France, UK, Germany, Sweden, The Netherlands and Switzerland. The aim of the programme was to provide recommendations for a new or additional PM measurement system to be used for EU Type Approval testing as well as advice on the development of future emission standards for both light and heavy duty vehicles. The objectives of the programme were to identify the best metrics for future particle measurements, determine which instruments and methods could utilize those metrics, investigate a test procedure for the measurement of particles during Type Approval tests and recommend a suitable test system or systems. Within the programme, a simultaneous comparison was made between 20 particle characterisation instruments.

8. The programme concentrated on the development of a methodology to measure solid (insoluble) particles in the size range of 20–300 nm for three reasons:

(i) The high probability of alveolar deposition, fast penetration into the vascular system and long residence time.

(ii) The availability of filters as highly efficient and technically proven tools to clean the exhaust gas of diesel to an extent that is new in air pollutant abatement.

(iii) Future diesels with PM emissions below the detection limit of the EPA 2007 method that will still emit millions of such particles <100 nm cm^{-3}.

9. It was argued that volatile particles will gradually cease to be an emission problem due to the use of sulphur-free fuels, low-sulphur lubricants and oxidation catalysts. When considering number concentrations, it was envisaged that the nucleation mode should be prevented to ensure consistent and repeatable measurements.

10. The main recommendation from the PMP programme was that two systems should be considered for future regulatory use: a modified 2007-PM (a gravimetric filter-based mass measurement system) and a CVS + thermodiluter + CPC (a number-based measurement system).