Transmitted by the expert from the UK

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Suitability of Particle Number Measurement For Regulatory Use

Summary
The PMP particle number measurement system has been demonstrated to be repeatable and reproducible between laboratories. The validation programme results clearly indicate the particle number performance level attainable by diesel particulate filter (DPF) equipped vehicles of all sizes and the vehicle-vehicle variability. The measurement system has proven itself to be stable and robust. Proposed Euro 5 PM limits can potentially be met with through-flow particulate aftertreatment devices which do not offer the same degree of control over ultrafine particle emissions as DPFs. Particle number measurement controls particle emissions across the size range enabling control of ultrafine emissions. The particle number measurement technique is therefore suitable and useful for regulatory purposes.

Background

The objective of the PMP was to develop and demonstrate new particle emissions measurement methods suitable for use in a type approval environment to supplement or replace the existing particulate mass measurement. The aim was to deliver measurement methods with improved sensitivity at low particle emissions levels (e.g. those delivered by wall-flow diesel particulate filter equipped engines/vehicles). These methods should enable setting of limit values to ensure adequate control of emissions of ultrafine particles. The decision as to whether to adopt such limit values is a political one and outside the scope of the PMP.

This document is submitted in response to OICA document GRPE-52-8 which raises a number of questions regarding the suitability of the measurement techniques developed by PMP for regulatory purposes.

Round Robin v Validation Programmes

The OICA paper argues that a Round Robin test should be conducted before new measurement techniques are adopted for regulatory use. As suggested by OICA this would involve inter-laboratory testing of a single vehicle with separate measurement systems at each laboratory, with each laboratory following written test procedures, but otherwise coming at the technique blind. OICA also argue that, as a second phase a large sample of vehicles should be tested to accumulate data for the purposes of setting limit values.

The validation test programme conducted by PMP has involved inter-laboratory testing of a single 'Golden Vehicle' with almost all laboratories using their own measurement system. Since the PMP particle number measurement technique is new there are however only a limited number of different measurement systems currently available which meet, or are close to meeting, the PMP specification. In addition a Golden System was circulated between laboratories to isolate the lab-lab variability from the system-system variability. Laboratories also tested additional vehicles to build up a dataset of the performance of different technologies in terms of particle number and revised particulate mass emissions. Participating laboratories followed written test procedures as suggested by OICA. Contrary to the approach suggested by OICA a ‘Golden Engineer’ visited all but two of the participating laboratories. Within the validation programme and other test programmes the particle number measurement equipment has been operated day-after-day for frequent tests and over shifts of up to 8 hours.

OICA cite the EPEFE studies and testing of the minor change to the EU test cycle (deletion of an initial unsampled 40 seconds of idling which was implemented at Euro 3) as precedents for Round-Robin testing prior to regulatory action. These did not however involve validating new sampling/measurement systems. A somewhat different approach is appropriate in this case since laboratories are being asked to implement equipment and procedures which are new to them and will therefore require some guidance to ensure they have correctly interpreted and applied the specified procedures. This is not dissimilar to the guidance a measurement system supplier would give to a laboratory when supplying a new measurement system.

More recent precedents which did involve validating such systems for regulatory use include the introduction of ISO 16183 partial flow sampling systems for Heavy Duty transient test particulate mass measurements and introduction of US Heavy Duty 2007 PM measurement procedures. Industry’s programme of testing to validate ISO 16183 involved a single Golden Sampling System supported by a Golden Engineer providing advice to ensure repeatable set-up and operation of the system. This programme did not involve additional measurement systems at laboratories or testing of Euro IV engine technology (the target for the measurement technique), as such it was less robust than the PMP light duty vehicle validation. Despite this it was considered sufficient to adopt ISO 16183 sampling systems into Heavy Duty Euro IV & V test procedures. The second recent precedent, adoption of US 2007 PM measurement procedures, involved validation testing in US-EPA’s own laboratories prior to its adoption in legislation.

So it can be seen that round-robin exercises have not generally been considered appropriate or necessary in adopting new sampling/measurement procedures either by industry or regulators.

Role of the Golden Engineer

OICA regard the presence of a Golden Engineer as compromising the validity of assessment of lab-lab variability (‘reproducibility’). In this they appear to have misunderstood the role of the Golden Engineer, which is to assist in interpretation of test procedures and ensure that laboratories do not diverge from following the written test procedures. The Golden Engineer is only present for the initial test at each laboratory and he does not set-up the test equipment. He merely views the laboratory’s set-up to confirm that it complies with the written procedures (this is consistent with a lab demonstrating compliance to a type approval authority). Once he has ensured that the procedures are being followed he departs and the laboratory continues testing.

The issues mentioned by OICA with the laboratory at which the Golden Engineer was not present were due to long distance shipping of the CPC, translation difficulties with the test protocol, time pressures and the time difference between the locations of the test laboratory and Golden Engineer. They did not affect the set-up of the measurement system or compromise the test results, but did result in some minor damage to one component of the measurement system. This would not occur once laboratories are familiar which the new equipment.

Number of Vehicles Tested

A total of 15 different vehicles have been tested in the PMP light duty vehicle validation programme. These included 5 conventional diesel vehicles, 6 DPF equipped vehicles, 3 lean-burn direct injection petrol engined vehicles and 1 conventional petrol vehicle. DPF equipped vehicle sizes ranged from class B (Peugeot 206) through to E (BMW 520d) and also light goods vehicles (Mercedes Vito, Mazda Bongo, M1 derivatives tested). Both additised DPF systems and catalysed DPF systems have been evaluated with at least 5 NEDC tests performed on each vehicle. OICA argue that a larger dataset is required for the setting of limit values.

Whilst proposing limit values is outside the remit of PMP it is presumed that regulators will primarily be interested in diesel vehicles with sub 5mg/km PM levels (proposed Euro 5 limit value). All of the DPF equipped diesels tested in this programme met this level. It should be noted that they all exhibited statistically similar particle number emissions results (including those of the light goods vehicle derivatives) with the exception of one vehicle which is known to have a more porous (cordierite) filter substrate. There does not appear to be any value in adding additional statistically similar vehicles to the dataset.

Comments on Further Work Recommended by OICA

Variability Within a Vehicle Type: It is assumed that Euro 5 vehicles will be fitted with DPFs. As discussed above particle number results for the DPF vehicles tested are statistically similar, there is therefore no reason to expect that variability within a vehicle model will be any different from the variability found between models.

Clean Particle Filter Performance: Differences of DPF fill state on particle number emissions have been determined as part of the validation programme, and maximum levels have been observed with an empty trap. The difference between these ‘empty-DPF’ and ‘full-DPF’ levels is very small compared with the differences between emissions from a non-DPF vehicle and could be accounted for in CoP procedures.

Assigned Deterioration Factors: Development of deterioration factors is outside the remit of PMP. It is presumed that the European Commission will have to consider deterioration factors for new vehicle technologies (including DPFs) in drafting its Euro 5 implementing measures. However available evidence suggests minimal reduction in DPF efficiency over time[1] so deterioration factors may be unnecessary.

[1] SAE 2004-01-0073

Regeneration Measurements: OICA are correct the PMP validation programme has not specifically addressed regenerations although some measurements have been made as part of JRC's investigative work. These and measurements elsewhere suggest that solid particle number emission increases during both active and passive regenerations are small compared with the differences between DPF and non-DPF vehicles. For this reason we do not regard inclusion of regeneration measurements at type approval as critical. Consequently the particle number measurement technique could be adopted for use under DPF storage conditions only. However, since OICA are keen to also conduct regeneration tests at type approval, further work could be conducted to demonstrate procedures for developing Ki factors, which could then be adopted at a second stage with an appropriate adjustment to limit values. Since increases in particle numbers during regenerations are not large, dilution settings in the GPMS need not change.

PN System Calibration Procedure: Calibration of the particle number system is based upon best aerosol practices. Aerosol scientists accept condensation nucleus counters as primary standards[2], and TSI has demonstrated an updated calibration method which links the electrometer method described, to NIST traceable standards. Minimum performance standards for the penetration, evaporation, temperature control and dilution of all of the measurement system elements are defined and simple daily validation/performance checks have been defined and conducted to demonstrate the consistent operation of the system. In addition a draft ISO standard on Condensation Particle Counter calibration has been prepared and is being progressed rapidly.

Air Quality/Impact Assessment: It is not within the remit of PMP to propose limit values or, consequently, produce an impact assessment. We support OICA's view that any emissions standard proposals should be accompanied by an impact assessment. The Commission have produced an impact assessment for their proposed Euro 5 standards. This proposal includes adoption of particle number limit values. Health benefit assessments implicitly assume that solid particle emissions will be reduced across the whole size range. This is what would be delivered by a particle number emission standard. Cost estimates explicitly assume that Euro 5 will result in adoption of wall-flow DPFs. A separate impact assessment would only be required if adoption of particle number standards were deleted from the Commission's proposal, since this is likely to result in a significant number of vehicles not being fitted with DPFs and hence not delivering the expected reductions in ultrafine particles. PMP validation test results show conventional diesel vehicles emitting as low as 11mg/km PM engine-out. Through-flow particulate aftertreatment devices have been shown to be capable of delivering 40-77% reductions in particulate mass (although studies show this to reduce over time), with reductions in particle number emissions of 60-80%[3]. In comparison the particle number emissions seen in this programme from vehicles equipped with efficient wall-flow DPFs are reduced by around 3 orders of magnitude (i.e. 99.9%) in comparison to non-DPF equipped vehicles. This makes their particle emissions comparable with petrol vehicles. Through-flow devices would therefore

[2] Liu et al: Intercomparison of different absolute instruments for measurement of aerosol number concentration. J. Aerosol Sci. 13: 429-450

[3] SAE 2006-01-0213, SAE 2005-01-0471 and 'Experience with the bypass-flow particulate trap with regard to the reduction of particulate number and mass for passenger car and truck applications' - R Bruck et al

enable today's best vehicles to meet proposed Euro 5 PM limits, whilst still emitting substantially higher numbers of particles than DPF equipped vehicles.

Vehicle to Vehicle Variability for CoP / In-Service Compliance: This has been discussed above. The sample DPF vehicles tested give statistically similar results and can thus be used to determine appropriate allowances for vehicle-vehicle variability. Despite PMP validation testing having only just finished, suitable measurement systems are already available on the market. The validation programme has demonstrated that labs can procure and install these systems in a matter of weeks with negligible lab downtime. The motivation for introducing a particle number measurement system is clear, it is necessary if regulators wish to ensure ultrafine particle emissions are well controlled and the anticipated health benefits are delivered. Particle number and particulate mass measure different properties and components of the vehicle exhaust. There is no fundamental correlation between the two, this will depend upon particulate chemistry and hence vehicle technology. Establishing corresponding limits would involve regulators examining the particle number emissions of technologies which currently meet proposed Euro 5 limit.

Conclusion

The PMP validation exercise has demonstrated that the particle number measurement method is a far more sensitive indicator of particle emissions performance than even the revised particulate mass measurement. Indeed particle number is sufficiently sensitive to indicate changes in the fill state of a DPF following regenerations. There is no evidence that the mass method is sensitive enough to indicate this.

The validation exercise was conducted along similar lines to recent industry validation programmes for new sampling system but with the additional demonstration of equivalence of alternative measurement systems. It shows that particle number measurement is repeatable and reproducible between labs when following the written test procedures. Assessment of additional measurement systems at laboratories has shown that alternative systems can deliver equivalent results.

DPF vehicles tested (the only vehicles meeting proposed Euro 5 PM limits) of all sizes, from B class to class III light commercial, showed statistically similar particle number results. The results therefore give a clear view of the technology capability and vehicle-vehicle variation.

Particulate mass results show that, with the application of through-flow type particulate aftertreatment systems, the best non-DPF vehicles could meet proposed Euro 5 PM standards, but without delivering the same reduction in particle number emissions (including ultrafine particles) delivered by DPFs. It is therefore likely that, in the absence of a particle number standard, a significant proportion of Euro 5 vehicles would exhibit relatively high ultrafine particle emissions.

Condensation nucleus counters are accepted by particle measurement experts as a primary measurement instrument. In addition to which, procedures for calibrating counters against electrometers and other particle counters have been drafted (including a draft ISO standard). In addition daily validation checks of the whole measurement system have been written and utilized during the validation exercise showing consistent, stable operation of the system.

The measurement system has shown itself robust enough to withstand heavy usage and repeated transportation with good stability throughout the validation programme.

There is no requirement for round-robin testing before the particle number measurement can be adopted in regulation. However an industry round-robin exercise would benefit manufacturers in better understanding the new procedures and ensuring that they are applying them consistently.

The particle number measurement procedure is therefore suitable for regulatory use.