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A study of emissions from a Euro 4 light duty diesel vehicle with the European particulate measurement programme

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ABSTRACT

The California Air Resources Board, CARB, has participated in a program to quantify particulate matter (PM) emissions with a European methodology, which is known as the Particulate Measurement Programme (PMP). The essence of the PMP methodology is that the diesel PM from a Euro 4 vehicle equipped with a Diesel Particulate Filter (DPF) consists primarily of solid particles with a size range greater than 23 nm. The PMP testing and the enhanced testing performed by CARB have enabled an increased understanding of both the progress that has been made in PM reduction, and the future remaining challenges for new and improved DPF-equipped diesel vehicles. A comparison of measured regulated emissions and solid particle number emissions with the results obtained by the PMP participating international laboratories was a success, and CARB's measurements and standard deviations compared well with the other laboratories. Enhanced measurements of the influence of vehicle conditioning prior to testing on PM mass and solid particle number results were performed, and some significant influences were discovered. For example, the influence of vehicle preconditioning on particle number results was significant for both the European and USA test driving cycles. However, the trends for the cycles were opposite with one cycle showing an increase and the other cycle showing a decrease in particle number emissions. If solid particle size distribution and total particle numbers are to be used as proposed in PMP, then a greater understanding of the quality and errors associated with measurement technologies is advisable.

In general, particle counting instruments gave results with similar trends, but cycle-to-cycle testing variation was observed. Continuous measurements of particle number concentrations during test cycles have given detailed insight into PM generation. At the present time there is significant variation in the capabilities of the particle counting instruments in terms of particle size and concentration.

Current measurements show the existence of a large number of volatile and semi-volatile particles of yet-to-be-resolved chemical composition in diesel exhaust, especially during DPF regeneration, and these particles are not included in the PMP methodology because they are smaller than 20 nm. It will be very challenging to improve our understanding of this class of diesel particulate matter.

1. Introduction and background

The California Air Resources Board (CARB) and the Joint Research Center of the European Commission (JRC) have collaborated on a number of research areas of mutual interest under a Memorandum of Understanding on *Emissions from Transport* signed on October 2005. One of those research topics is the Particulate Measurement Programme (PMP) launched under the auspices of the United Nation's Economic Commission for Europe - Group of Experts on Pollution and Energy, (Andersson and Clark, 2004; Andersson et al., 2007). The California study conducted emission testing of the PMP's Golden Vehicle (GV) at its Haagen-Smit Laboratory (HSL) in Los Angeles. The essence of the PMP methodology is that the diesel PM from a Euro 4 vehicle with a Diesel Particulate Filter, DPF, consist primarily of solid particles with a size range greater than 23 nm. The testing was an informal participation by CARB in the ligh-duty vehicle Inter-laboratory Correlation Exercise (ILCE_LD) that PMP conducted formally including 11 laboratories from Europe and Asia. The GV was a reference standard that was circulated around to all of the participating laboratories.

The California testing was unique and expanded the ILCE_LD by including enhanced emissions testing which was not originally part of the PMP. The present paper is primarily concerned with results obtained with the use of the PMP, however results from some

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enhanced emission testing are also described in the paper. Also, the testing and reporting of the GV results (Ayala et al., 2009) was the culmination for a number of initial pilot investigations completed by CARB to assess the PMP protocol for heavy-duty vehicle classes (Ayala et al., 2007; Herner et al., 2007, 2009; Robertson et al., 2007; Zhang et al., 2008). A recent investigation of the PMP method for heavy-duty diesel engines was conducted in partnership with researchers from the University of California Riverside, the University of Minnesota, Matter Engineering, TTM, and Ricardo (Durbin et al., 2008). The investigation of the PMP methodology as a new measurement tool is the primary focus of the present paper, but a detailed study of tailpipe emissions from the GV is also described. The important research objectives were the following: (a) Compare CARB laboratory test results for criteria gases, particle mass, and particle number with results from PMP participating laboratories; (b) Evaluate the effects of vehicle soak-time conditioning on PM and particle number results; (c) Evaluate the effects of vehicle pre-conditioning cycles on PM and particle number results; (d) Compare various particle sampling instruments; (e) Determine some physical and chemical characteristics of the PM emissions; and (f) Study the emissions during regeneration of the DPF. CARB believes the areas of DPF regeneration and the determination of the physical and chemical characteristics of PM emissions need further study.

2. Test vehicle, the measurement systems, and test procedures

The GV employed in the testing was a Peugeot 407 diesel passenger car equipped with a DPF, and it represents the most mature DPF technology present on the market and fully meets EURO4 emission standards (Blanchard et al., 2002; Giechaskiel et al., 2007, 2008; Quigley and Seguelong, 2002; Coroller and Plassat, 2003; Mohr et al., 2006). The DPF system consists of an oxidation catalyst upstream of an uncoated silicon carbide wall-flow DPF and a cerium-based fuel-borne catalyst to reduce the DPF regeneration temperature. The cerium based fuel-born catalyst is housed separately from the fuel tank, and the method of doping the fuel with fuel-born catalyst is controlled by the vehicle's on-board dosing system. The fuel used for the California testing was Ultra-Low Sulfur Diesel fuel, and no attempt was made to duplicate the diesel fuels employed at the other participating laboratories.

At the present time the PMP methodology only attempts to measure solid particles with a diameter that is greater than 23 nm. PMP targets this size of particle for practical reasons and in an effort to reduce the variability in the measurement. It is recognized that diesel PM consists of large numbers of semi-volatile particles in the sub-23 nm size range. It is also well known that semi-volatile particles can contribute to PM measurements based on the gravimetric measurement. The role of sub-23 nm particles has to be studied more extensively for possible health effects. Therefore, there will likely be a considerable amount of further research as improved diesel emission reduction technology is introduced into vehicle fleets.

The GV was shipped with instrumentation described as the Golden Particle Measurement System, GPMS, which was slightly modified and enhanced by CARB due to a failure of a GPMS instrument during the testing. Fig. 1 shows the major components of test set-up for particle measurements. It consisted of the following major parts: (a) A Constant Volume Sampling Tunnel; (b) A cyclone with a 2.5 μm size cut-point; and (c) Five independent particle counting systems with different features. Three of the counting systems contained an evaporation tube (ET) while two did not, and this setup allowed us to differentiate between solid and total (volatile, semi-volatile, and solid) particles. The role of the ET is to remove volatile

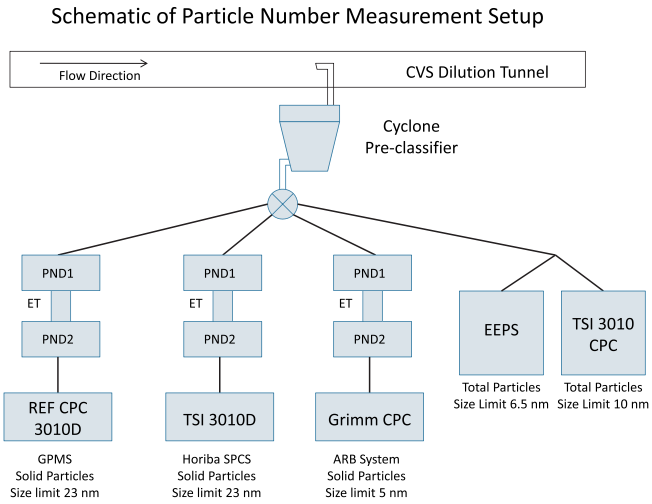

Fig. 1. Schematic of typical sampling setup during ARB emission testing.

and semi-volatile particles before the particles in the exhaust reach the PMP measuring instrument. Volatile and semi-volatile particle formation is a strong function of sampling conditions and including them in an exhaust sample has potential to lead to high variability in the measurement, something the PMP was charged to improve upon. The particle counting systems also had different particle size resolutions, and this feature gave additional information concerning particle size. It should be mentioned that the California testing included particle instruments not used by the other participating laboratories, and this enhancement to the testing program allowed for a comparison of the other instruments to the PMP instruments. A list of the various instruments is given in Table 1.

The test set-up also included measurement of regulated exhaust emissions (HC, NO_X, CO, PM mass) and CO_2. The sampling system, calculations, calibrations, and quality control conformed to the requirements of 40 CFR 86.[1] Sampling and calculations for PM mass on TX40 and Teflon filters conformed to 40 CFR 1065.[2] In addition to sampling for the regulated pollutants, CARB collected samples for analysis of organic and elemental carbon (OC/EC) and metals. Quartz fiber filters were collected at ambient temperature for determination of OC/EC (Ayala et al., 2008).

Exhaust emission tests were conducted to study a number of the following issues:

- The comparability of CARB laboratory results over the New European Driving Cycle (NEDC), with results from PMP participating laboratories.
- The results and performance of the PMP protocols using the Federal Test Procedure cycle, FTP.
- The effects of vehicle soak time on PM and particle number results.
- The effects of vehicle pre-conditioning cycles on PM and particle number results.
- The comparability of various particle sampling instruments with each other.

[1] Code of Federal Regulations: PART 86-CONTROL OF EMISSIONS FROM NEW AND IN-USE HIGHWAY VEHICLES AND ENGINES 86.084-40, Automatic expiration of reporting and recordkeeping www.access.gpo.gov/nara/cfr/waisidx_04/40cfr86_04.html.

[2] Code of Federal Regulations: PART 1065-CONTROL OF EMISSIONS FROM NEW AND IN-USE HIGHWAY VEHICLES AND ENGINES 1065.084-40, Automatic expiration of reporting and recordkeeping www.access.gpo.gov/nara/cfr/waisidx_04/40cfr1065_04.html.