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Emissions from a diesel car during regeneration of an active diesel particulate filter

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ABSTRACT

The California Air Resources Board (CARB) and the Joint Research Center of the European Commission (JRC) have collaborated on emissions testing of a light duty diesel vehicle, which is Euro 4 compliant and comes equipped with a diesel particulate filter (DPF). The California testing included an investigation of the regeneration of the DPF over cruise conditions and NEDC test cycles. DPF regeneration is caused by the buildup of soot in the filter, and for the present test vehicle the regeneration process is assisted by a fuel borne catalyst. Regulated exhaust emissions increased substantially during the regeneration events; however, PM emissions levels were below California LEVII emissions standards. There was a very large increase of volatile particles between 5 and 10 nm, and these volatile particles were generated during all of the observed regeneration events. It appears that the particle number instruments that use the PMP methodology do not capture the PM mass increase during DPF regeneration; however, for one regeneration event there was an apparent large increase in solid particles below the PMP size limit. The PM mass increase associated with regeneration appears to be due to semi-volatile particles collected on filters. During the testing, the regeneration events exhibited considerable variations in the time for regeneration as well as the amount of PM emissions. From this investigation, several questions have been posed concerning the emission of very small (<20 nm) volatile and solid particles during DPF regeneration that need further investigation.

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. The CARB investigation was centered on a new solid particle number emission measurement protocol developed under the Particulate Measurement Program (PMP). The PMP was launched under the auspices of the United Nation's Economic Commission for Europe-Group of Experts on Pollution and Energy (Andersson, Giechaskiel, Muñoz-Bueno, Sandbach, & Dilara, 2007). In addition to solid particle number, measurements of regulated emissions, DPF regeneration emissions, evaporative emissions, and the chemical characterization of particle mass

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emissions were conducted. The PMP methodology has been shown to be 20 times more sensitive than traditional gravimetric methods (Andersson et al., 2007), and it is planned to be an important complementary element to measure and analyze diesel and gasoline particle mass and number emissions for new vehicles to be certified for emissions compliance for Europe in the near future. Extensive testing of the newly proposed PMP sampling protocol was accomplished in Europe and Asia to verify the applicability and practicality of the proposed methodology at different laboratories.

A standard vehicle with a DPF, the ''Golden Vehicle'' (GV), was used as a reference and the GV was sent to Los Angeles in October 2006 for testing at the CARB's Haagen Smit Laboratory. The Haagen Smit Laboratory has a newly equipped test cell dedicated to clean vehicle testing, and the testing by CARB provides JRC with an additional data point for its inter-laboratory correlation exercise. The complete testing and reporting of the GV results have been placed in a CARB report (Ayala et al., 2008), and the readers of this paper are encourage to download this report in order to obtain more details. In addition to the GV investigation CARB has completed detailed PMP studies for heavy duty vehicles (HD), which involved both laboratory and on road testing with the use of the PMP methodology (Ayala et al., 2007; Herner et al., 2009; Herner, Robertson, & Ayala, 2007; Robertson, Herner, Ayala, & Durbin, 2007; Zhang, McMahon, Wei, Huai, & Ayala, 2008). Therefore, the GV program has advanced the knowledge of particulate matter emissions, and it will be very helpful in future plans and actions for clean cars.

Besides the testing of the PMP methodology, enhanced emissions testing was carried out, which was not part of the PMP. The enhanced emissions testing program included measurements of particles generated during regeneration events of the DPF and of the chemical characteristics of the particle mass emissions. Both regeneration events and chemical characteristics are not part of regulated emissions testing; however, they may be considered for regulation in the future. At the present time there are considerable interests in emissions from DPF regeneration events (Andersson et al., 2007; Bergmann & Kirchner, 2009; Bikas & Zervas, 2007; Cauda, Hernandez, Fino, Saracco, & Specchia, 2006; CRC Report, 2009; Giechaskiel et al., 2007), but it is difficult to directly relate the present work to these previous studies, since the type of DPF, test procedures, and instrumentation are different. DPF technology is a changing field that will evolve substantially in the coming years, and the current CARB verification process for DPF regeneration is specific to each model and manufacturer of DPFs.

2. The Golden Vehicle and the testing equipment

The GV is a 2004 Peugeot 407 direct injection diesel passenger car equipped with a DPF, and it had a 2 l, turbocharged, and four cylinder engine. The GV represents a mature DPF technology present on the market and fully Euro 4 compliant (Blanchard et al., 2002; Cauda et al., 2006; CRC Report, 2009; Giechaskiel et al., 2007; Quigley & Seguelong, 2002). 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 temperature needed for DPF regeneration. 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. A regeneration event is triggered by pressure drop across the DPF, and the vehicle's engine control system utilizes strategies such as late cycle fuel-injection and exhaust gas recirculation (EGR), shut-off to generate an exotherm in order that diesel particles captured by the DPF can be oxidized during regeneration. The ideal process would oxidize hydrocarbons to carbon dioxide and water; however, for real world events both solid and volatile particles are generated in large numbers, as well as increased gaseous emissions. During the CARB testing three DPF regeneration events were observed, and each of these regeneration events had a different character due to the different type of tests that were being carried out. The specific details of each regeneration event have some different characteristics and they will be described in the Results section.

The GV was shipped with instrumentation described as the Golden Particle Measurement System (GPMS), which was enhanced and slightly modified by CARB (Ayala et al., 2008). Fig. 1 shows the major components of the particle measurement system as used, and it consisted of the following parts: (a) a constant volume sampling full-flow dilution tunnel of the type used commonly for vehicle/engine emissions testing for research and certification; (b) a cyclone with a 2.5 μm size cut-point, which is a new feature of new test methods proposed in the US and Europe, and all particle measurements were taken after the cyclone; (c) five independent particle counting systems with different features; however, the GPMS Gold CPC failed and it was replaced with a CARB reference CPC during the testing. Three of the counting systems contained an evaporation tube (ET) or volatile particle remover (VRP) as recommended by the PMP protocol for removal of volatile particles, while two did not, and this setup allowed us to differentiate been solid and total particles. (Note: A summary of the various instruments is given in Table 1.) The instruments used to measure solid particles are connected to particle number diluters, and these are indicated by the letters PND1 and PND2 in Fig. 1.

During the last two decades there have been considerable advances in instrumentation to measure particulate matter from combustion sources (Bukowiecki et al., 2002; Burtscher et al., 2001), and diesel PM has been studied in detail due to the health effects associated from this source (Wichmann & Peters, 2000). Some examples of the progress that has been made for measurements in diesel engines are given in the following references, Moosmuller et al. (2001a, 2001b), Matter, Siegmann, and Burtscher (1999), and Bukowiecki et al. (2002), and for the use of CPCs in diesel engine research see Ref. Sem (2002). Of particular importance to the present paper is the use of ETs to distinguish between solid particles and total particles (solid plus volatile particles) (Burtscher, Kunzel, & Huglin, 1998). Since emissions from diesel engines are a