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Impact of cold temperature on Euro 6 passenger car emissions ☆

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ABSTRACT

Hydrocarbons, CO, NOx, NH_3, N_2O, CO_2 and particulate matter emissions affect air quality, global warming and human health. Transport sector is an important source of these pollutants and high pollution episodes are often experienced during the cold season. However, EU vehicle emissions regulation at cold ambient temperature only addresses hydrocarbons and CO vehicular emissions. For that reason, we have studied the impact that cold ambient temperatures have on Euro 6 diesel and spark ignition (including: gasoline, ethanol flex-fuel and hybrid vehicles) vehicle emissions using the World-harmonized Light-duty Test Cycle (WLTC) at −7 °C and 23 °C. Results indicate that when facing the WLTC at 23 °C the tested vehicles present emissions below the values set for type approval of Euro 6 vehicles (still using NEDC), with the exception of NOx emissions from diesel vehicles that were 2.3–6 times higher than Euro 6 standards. However, emissions disproportionally increased when vehicles were tested at cold ambient temperature (−7 °C). High solid particle number (SPN) emissions ($>1 \times 10^{11}$ # km^{-1}) were measured from gasoline direct injection (GDI) vehicles and gasoline port fuel injection vehicles. However, only diesel and GDI SPN emissions are currently regulated. Results show the need for a new, technology independent, procedure that enables the authorities to assess pollutant emissions from vehicles at cold ambient temperatures.

Harmful pollutant emissions from spark ignition and diesel vehicles are strongly and negatively affected by cold ambient temperatures. Only hydrocarbon, CO emissions are currently regulated at cold temperature. Therefore, it is of great importance to revise current EU winter vehicle emissions regulation.

1. Introduction

Winter season is associated with high pollution episodes (Custódio et al., 2016; Wang et al., 2017). Recent seasonal studies have shown that in some urban areas the highest levels of NOx, NH_3, CO and PM occur in the cold season (Hofman et al., 2016; Hama et al., 2017). Those studies, as well as the recent report presented by the European Environment Agency (EEA, 2014), indicate that transport sector is one of the main sources of these air pollutants. Moreover, they are (themselves or as precursors) among the most problematic pollutants in terms of harm to human health in Europe: PM, ground-level O_3 and nitrogen dioxide (NO_2) (EEA, 2015).

Urban PM composition is strongly influenced by vehicle exhaust (Custódio et al., 2016; Giorio et al., 2015; Jeong et al., 2016; Pey et al., 2010). Vehicles contribute to both organic and inorganic fraction of the PM via: i) primary PM emissions and ii) emission of precursors of secondary organic aerosols (SOA) and secondary inorganic aerosols, such as volatile organic compounds (VOCs), NOx or NH_3 (Amanatidis et al., 2014; Gordon et al., 2014; Link et al., 2017; Platt et al., 2014, 2017). Moreover, transport sector is one of the dominant sources of NOx, CO and non-methane volatile organic compounds (NMVOC) in Europe; pollutants that together with methane are the main ground-level ozone precursors (EEA 2014). Road transport emissions account for 40.5% NOx, 26.5% CO and 14.6% NMVOC of the total emissions in EEA-33.

European vehicle emissions regulation has become more stringent over the years aiming at improving Europe's air quality. Emissions of THC, NMHC, CO, NOx, solid particle number (SPN; solid particles with a diameter >23 nm) and particle mass (PM) are now a days regulated under the Type 1 test for Euro 6 vehicles. Furthermore, with the implementation of the new regulation in EU

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(EC, 692/2008), this test will be performed following the WLTP, where tests must be performed at 23 ± 5 °C using the worldwide harmonized light-duty driving test cycle (WLTC) (UNECE, GTR 15). However, emission limits and testing procedure at cold ambient temperature have not seen significant changes since it first introduction in 1998 (EC, 98/69).

The Type 6 test (name commonly used in EU to refer to the cold temperature test) was introduced "as a measure against air pollution by emissions from motor vehicles at cold ambient temperatures". The test is carried out only on positive-ignition light-duty vehicles on a chassis dynamometer at −7 ±3 °C over the Urban Driving Cycle (UDC; first of the two phases constituting the New European Driving Cycle, NEDC), and only foresees the analysis of CO and THC. It is worth noticing that CO and THC emissions must be, respectively, lower than 15 g km^{-1} and 1.8 g km^{-1}, which are more than 15 times higher than those allowed during Type 1 test performed at 23 ± 5 °C.

Similar procedures are applied at cold temperature in the USA (CFR 1066 Subpart H) (US. EPA), South Korea (MOE, 2014) and China (China 6, 2017). They present a number of similarities with the European Type 6 test, including the temperature at which the test is performed (-7 °C) and the determination of the road-load (which can be either determined at −7 °C or adjusting the driving resistance by decreasing 10% the coast-down time), but there are important differences as well. For instance, while the procedures applied in USA and China require petrol and diesel vehicles to be tested al low temperature, those in force in EU and Korea only apply to positive-ignition vehicles. Moreover, China has been the first country to include NOx measurements and emission limits at cold temperature (China 6, 2017).

A new and representative procedure that enables the authorities to assess the emissions from vehicles at low ambient temperatures needs to be defined and the present work addresses a number of important issues that should be considered in the future low temperature testing procedure in EU. Issues such as: The use of WLTC, a cycle that is more representative of real world driving; the use of a procedure that is fuel and technology independent applied to spark-ignition, compression-ignition and hybrid light-duty vehicles; the measurement of criteria pollutant emissions present in vehicle exhaust, other than THC and CO, namely: NOx and SPN.

Vehicle emissions of NH_3 - a precursor of secondary inorganic aerosol in the atmosphere (Kim et al., 2000; Phan et al., 2013) - and nitrous oxide (N_2O) - a powerful greenhouse gas and the single most important ozone-depleting substance (ODS) (Ravishankara et al., 2009)- have been related to the use of catalytic converters such as: as Three-Way Catalyst (TWC), NOx Storage Catalyst (NSC), Diesel Oxidation Catalyst (DOC), Selective Catalytic Reduction (SCR) and Lean NOx Trap (LNT) (Guan et al., 2014; Ko et al., 2017; Suarez-Bertoa et al., 2014; Suarez-Bertoa and Astorga 2016a; Wallington and Wiesen, 2014). NH_3 vehicle emissions are regulated in Korea (MOE, 2014), and N_2O emission standards have recently been introduced by the U.S. Environmental Protection Agency (EPA) under the Clean Air Act (EPA, 2015) and in China with the introduction of China 6 (China 6, 2017). However, NH_3 and N_2O emissions from passenger cars are not regulated in EU. Therefore, the use modern vehicles equipped with these after-treatments brings new environmental and health concerns since unknown amounts of NH_3 and N_2O will be emitted. For that reason, in addition to criteria pollutants (CO, THC, NOx, SPN) and CO_2, emissions of NH_3 and N_2O at −7 °C and 23 °C are also discussed here. The presented results are of great interest to help extending and updating vehicle emission inventories and databases which often lack of data for cold temperature emissions or rely on those obtained using the off-dated UDC, which is not representative of realistic driving conditions.

2. Experimental section

Twelve passenger cars from the European market (see Table 1), were tested at the Vehicle Emission Laboratory (VELA) of the European Commission Joint Research Centre (EC-JRC) Ispra, Italy. The facility includes a climatic test cell with controlled temperature and relative humidity (RH) to simulate ambient conditions (temperature range: −10 to 35 °C; RH: 50%). Duplicated tests were performed at 23 and -7 °C on a chassis dynamometer (inertia range: 454–4500 kg), designed for two and four-wheel drive light-duty vehicles (two 1.22 m roller benches – Maha GmbH, Germany). The emissions were fed to a Constant Volume Sampler (CVS, Horiba, Japan) through a heated transfer-line (~90 °C). A critical Venturi nozzle was used to regulate the flow (CVS flow range: 3–30 m^3 min^{-1}). A series of thermocouples monitored the temperature of the oil, cooling water, exhaust, and ambient conditions.

The selected fleet features a wide range of engine power, displacement, mileage and after-treatment systems, typical of the modern European fleet. It included: Five Euro 6 diesel vehicles (3 equipped with SCR (DV1-DV3) and 2 equipped with LNT (DV4 and DV5)); five Euro 6 gasoline vehicles (GV1-GV5; all equipped with TWC and one (GV3) also equipped with NSC); one Euro 6 gasoline hybrid (HV; equipped with TWC); and one Euro 5 flex-fuel vehicle (FFV; equipped with TWC).

Tests were performed using the WLTC at 23 and -7 °C ambient temperature. The WLTC (UNECE, GTR 15) was designed to be representative of real world driving conditions based on real world vehicle trips from several countries (Tutuianu et al., 2015). It is a cold start driving cycle consisting of four phases with different speed distributions: low speed (589 s), medium speed (433 s), high speed (455 s) and extra-high speed (323 s) phases (see Fig. 1). It reaches a maximum speed of 131.3 km h^{-1}, lasts 1800 s and is ~23.3 km long. Before being tested, vehicles were kept inside the climatic cell under the needed temperature (23 or −7 °C) for at least 6 h.

As indicated in the different regulations, vehicle road-load needs to be adjusted for low temperature testing. In this study, driving resistance was adjusted decreasing the coast-down time estimated at 23 °C by 10% for all the tests at −7 °C, including those with the hybrid vehicle, HV.

CO_2 emissions from hybrid and common diesel and gasoline vehicles are calculated following different procedures at 23 °C (UNECE, GTR 15). The high voltage battery of a hybrid vehicle can be at different state of charge (SOC) at the beginning of the test. For that reason, a series of tests under the so-called charge sustaining protocol are needed to calculate a correction factor for CO_2 emissions from hybrid vehicles (UNECE, GTR 15). In this study HV was tested using the hybrid vehicles protocol at 23 °C and at −7 °C.

Vehicles were tested using reference fuels as stated in Global Technical Regulation 15 (GTR 15) for tests at 23 °C and UNECE Regulation 83 for tests at −7 °C. EU regulation does not prescribe a reference diesel for test at low temperature because this test is not applicable for diesel vehicles. Grade D (Cold Filter Plugging Point (CFPP) −10 °C) winter diesel was then chosen for tests at −7 °C. Besides being tested on E5, FFV was tested on E85 (summer blend, containing 85% vol ethanol and 15% vol gasoline) at 23 °C and on E75 (winter blend, containing 75% vol ethanol and 25% vol gasoline) at −7 °C.

Regulated gaseous emissions were measured using an integrated setup (MEXA-7400HTR-LE, HORIBA) that analysed diluted gas from the CVS. Gaseous emissions were analysed from a set of Tedlar bags. The bags were filled with diluted exhaust from the CVS (Automatic Bag Sampler, CGM electronics) and concentrations were measured using non-dispersive infrared (for CO/CO_2), a chemiluminescence (for NOx) and a heated (191 °C) flame ionization