Fuel 233 (2018) 620–631

Contents lists available at ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel

Full Length Article

Comparative study on low ambient temperature regulated/unregulated emissions characteristics of idling light-duty diesel vehicles at cold start and hot restart

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ARTICLE INFO

Keywords:
Low ambient temperature
Cold start
Hot restart
Unregulated emission
Idle
Diesel vehicle

ABSTRACT

Since it is common for vehicles with idle engines to be stored indoors during the winter season to remain warm, better constraints are needed for idling emissions at low ambient temperature. CH_4 (methane), C_2H_6 (ethane), C_2H_4 (ethylene), HNCO (isocyanic acid), N_2O (nitrous oxide), NH_3 (ammonia), C_3H_6 (propylene), and HCHO (formaldehyde) from many unregulated exhaust emissions were selected and measured by a Fourier Transform Infrared Spectroscopy (FTIR) analyzer in this study. This paper investigates the idling regulated and unregulated emissions of Euro 5/6 diesel vehicles at cold start and hot restart near 0 °C conditions. The impact of cold start and hot restart on NO_x idling emissions was lower than CO and HC idling emissions in diesel vehicles. With regard to unregulated emissions, high fuel–air equivalence ratios and longer ignition delay in the idle cold start condition may increase incomplete combustion and affect the thermal cranking processes, leading to the increase of CH_4, C_2H_4 and C_3H_6. Furthermore, as the formation of N_2O is considerably affected by the equivalence ratio and cylinder temperature, a high fuel-air equivalence ratio at low ambient temperature in the cold start condition resulted in the increase of N_2O emissions.

1. Introduction

As the importance of urban air quality and human health have been highlighted around the globe, vehicle emissions regulations have become more stringent, following the leads of the European Union (EU) and the United States (US) California Air Resources Board (CARB) [1–3]. In particular, diesel engines suffer from Nitrogen Oxide (NO_x) emissions due to the lean combustion process and high in-cylinder temperature. Hence, car manufacturers have tended to improve the Engine Management System (EMS) and After-treatment systems, such as the two-stage EGR (Exhaust Gas Recirculation), Lean NO_x Trap (LNT) and Selective Catalytic Reduction (SCR) to meet the Euro 6 NO_x emissions regulations [4–6]. Despite all these efforts, NO_x emissions in Real Driving Emission tests (RDE) have been significantly higher in comparison with various driving cycles on a chassis dynamometer. The New European Driving Cycle (NEDC), as the certificate vehicle test cycle, has been changed into the World-harmonized Light-duty vehicle Test Cycle (WLTC) from September 2017 to better reflect real driving conditions [7,39]. Furthermore, the RDE test procedure has been enacted by September 2017 through several years of monitoring stages. Alongside the RDE test procedure, the European commission has introduced 'Not-to-exceed' (NTE) emissions limits that have applied in the RDE tests. The results of the RDE emissions for the entire RDE trip and the urban part alone have to remain below the NTE emissions limits ($NTE_{pollutant}$ = Conformity Factor $(CF)_{pollutant}$ × Euro-6) [39]. Specifically, car manufacturers should bring the CF down within 2.1 from September 2017. In addition, CF will then have to reach 1.5 of CF by January 2020. In other words, NO_x emissions in the RDE have to be lower than 168 mg/km from September 2017 and 120 mg/km by January 2020.

Diesel exhaust emissions contain many unregulated emissions species in addition to regulated exhaust emissions, such as Hydrocarbon (HC), Carbon monoxide (CO), NO_x, and Particulate Matter (PM) [8,9]. Although there are many vehicle-related unregulated emissions that significantly adversely affect human health and the global environment, this study selected CH_4 (methane), C_2H_6 (ethane), C_2H_4 (ethylene), HNCO (isocyanic acid), N_2O (nitrous oxide), NH_3 (ammonia), C_3H_6 (propylene), and HCHO (formaldehyde) from a variety of unregulated exhaust emissions. First, methane is a strong greenhouse gas, with a greenhouse gas effect 21 times that of Carbon dioxide (CO_2); methane also tends to cause headaches, nausea, and dizziness with inhalation [10,11]. Ethane, excluding an adequate supply of oxygen to the lungs,

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https://doi.org/10.1016/j.fuel.2018.05.144
Received 26 December 2017; Received in revised form 9 May 2018; Accepted 29 May 2018

also leads to dizziness. Ethylene also results in headaches, nausea, dizziness, and unconsciousness, and serves as an ozone formation agent [10,11]. Isocyanic acid might be an irritant to the skin, respiratory system and mucous membranes [10,11]. Nitrous oxide has a global warming effect that is 298 times greater than CO_2, and it is the single greatest contributor to ozone depletion [12]. Ammonia, having a distinct pungent and irritating odor, causes severe irritation of the eyes, nose and throat [12]. Propylene is regarded as a Volatile Organic Compound (VOC) and can bring about mutagenic effects. Formaldehyde is classified as carcinogenic by the National Institute for Occupational Safety (NIOSH) and the World Health Organization (WHO) and affects pregnancy and the reproductive system [10,11]. The reasons why these unregulated emissions were adopted in this study are their harmful effects to human health and the environment, as mentioned above, and their reliability, of which Fourier Transform Infrared Spectroscopy (FTIR) guarantees quantitative unregulated emissions as listed above.

Although type-approval vehicle emissions tests have been performed between 20 and 30 °C, there are many regions in Asia, Europe, and North America in which subzero ambient temperatures are common in the winter season [13]. Moreover, allowing an engine to idle prior to driving a vehicle in the winter season is more common in order to prevent engine damage [14,15]. Idling during parking and stopping for periods of time are also more prevalent to keep the engine and vehicle compartment warm [16,17]. Emissions during cold start account for a substantial part of vehicle emissions, especially in subzero ambient temperature conditions [18,19]. Therefore, examining the idling emissions of light-duty diesel vehicles at cold start could be required to ensure cleaner urban air quality.

With regard to RDE regulation, idle fraction of RDE urban test should be within the range of 6–30 %. In fact, idle time in the real world driving condition had wide fluctuations because idle time in the real world driving condition is greatly affected by the traffic condition. Idling due to other purposes such as keeping engine and indoor warm may take up overall idling time as non-negligible portions. Regarding heavy-duty truck, previous researches indicated that 10 min of idling per day will spend more than 27 Gal (102 L) of fuel per year. Fuel consumption at idle is estimated to be approximately 0.8–2 billion gal per year. Long-duration truck engine idling emits 11 million tons of carbon dioxide, 200,000 tons of oxides of nitrogen, and 5000 tons of particulate matter [17,40].

There have been several studies focusing on unregulated emissions, low temperature emissions, cold start emissions, and idle emissions from diesel engines. Agarwal et al. studied unregulated emissions and health risks from diesel engines with a biodiesel and methanol blend. They reported an increasing trend for some unregulated emissions, such as formaldehyde, acetaldehyde, ethanol, and n-butane, from blends of biodiesel [10]. Dardiotis et al. investigated the cold start gaseous emission performance of late technology passenger cars at low ambient temperatures. They revealed that diesel vehicles without any NO_x after-treatment system exhibited increased NO_x emissions over the NEDC at subzero temperatures, but that vehicles with SCR indicated superior NO_x reduction performance [4]. Yin et al. examined idling emissions characteristics of a light-duty diesel van at various altitudes. They reported that CO emissions increased with the increase of altitude, but NO_x emissions were not affected by altitude. Additionally, they found that larger particle numbers were exhausted at the high altitude [14]. Compared to other conditions, many studies have been conducted on the effect of cold start on emissions. Reiter et al. examined the problem of cold start while focusing on mobile source emissions levels. They mentioned that trip chaining (to keep engines warm) and shifting to non-motorized modes for shorter driving, where the cold start effect can dominate emissions, are important issues in the transportation sector. They also explained that cold start emissions account for a high portion of the total transportation-related CH_4, N_2O, and VOC emissions [18].

Whereas each of above mentioned studies described unregulated emissions, low temperature emissions, cold start emissions, and idle emissions, almost no study has been performed thus far on the low ambient temperature regulated and unregulated emissions characteristics of idling light-duty diesel vehicles for cold start and hot restart. In addition, many studies about gaseous emissions over the various vehicle emission test cycles and real world driving conditions have been investigated by many researchers, but there have been few studies about idling emissions. Besides, most of studies about idling emissions were conducted from heavy-duty diesel vehicles or trucks. As this research about idling emissions from light-duty diesel vehicles is reported, it will contribute to attracting more interests for idling emissions, providing the environmental effects of idling emissions from light-duty diesel vehicles and suggesting the policy to reduce idling emissions. Hence, this research highlights some important inferences in terms of real-time unregulated emissions emitted by idling diesel vehicles in the winter season. Additionally, this paper provides an approach and emphasizes the necessity for optimizing the after-treatment system and EMS during the idle state for low emissions so that diesel vehicles can fulfill forthcoming emission legislations, including in idle and low ambient temperature conditions. In the present paper, the recent Euro 5/6 diesel vehicles equipped with the Diesel Oxidation Catalyst (DOC) or LNT and the Diesel Particulate Filter (DPF) were tested at cold start and hot restart near 0 °C conditions. Real-time regulated and unregulated emissions were measured by an FTIR analyzer for an idling state. The results and discussions were described from a comparative analysis of each vehicle and start condition.

2. Experimental apparatus

2.1. Engine, after-treatment system, and test fuels

The specifications of three light-duty diesel engines and vehicles used in this study are described in Table 1. An engine named vehicle 1 is a 1.6-L turbocharged, in-line 4-cylinder and common rail direct injection (CRDI) diesel engine. This engine is equipped with a variable geometry turbine (VGT) and a common rail fuel injection system. Vehicle 1's after-treatment system is a catalyzed DPF (CPF) with DOC and DPF to meet the Euro 5 regulation. Vehicle 2 is an upgraded version of vehicle 1 to meet the Euro 6 regulation. The main differences between vehicle 1 and vehicle 2 are the transmission type (6 automatic or 7 dual-clutch) and after-treatment system (DOC or LNT). Vehicle 3's engine has a larger displacement and heavier weight than vehicle 1 and 2; it is a 2.2-L turbocharged inline 4-cylinder CRDI system. This vehicle's after-treatment is LNT and DPF for Euro 6 regulation compliance. All the after-treatment systems of the test vehicles were located at the close-coupled position. Additionally, the test fuel was analyzed by K-petro (Korea Petroleum Quality & Distribution Authority), with verification that the test fuel corresponded to the fuel standard regulation. The properties of the test fuel are shown in Table 2.

Table 1
Specification of test vehicles.

Vehicle	1	2	3
Engine type	eVGT + CRDI	eVGT + CRDI	eVGT + CRDI
Displacement (cm^3)	1582	1582	2199
Max. power (ps)	128 ps	136 ps	202 ps
Max. torque (kg·m)	26.5 kg·m	30.6 kg·m	45.0 kg·m
Combined fuel economy (km/L)	16.2	17.3	13.8
CO_2 emission (g/km)	120	111	144
Unladen weight (kg)	1275	1365	1691
Emission standard	Euro 5	Euro 6	Euro 6
Transmission type	Auto, 6	DCT, 7	Auto, 6
After-treatment system	DOC + DPF	LNT + DPF	LNT + DPF