

An Investigation into Cold Start Emissions from Compression Ignition Engines using EU Legislative Emissions Test Procedures

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ABSTRACT

Diesel (compression ignition, CI) engines are increasingly exploited in light-duty vehicles, due to their high efficiency and favorable characteristics. Limited work has been performed on CI cold-start emissions at low temperatures. This paper presents a discussion and a brief literature review of Diesel cold-start emissions phenomena at low ambient temperatures and the results of tests performed on two European light-duty vehicles with Euro 5 CI engines. The tests were performed on a chassis dynamometer within an advanced climate-controlled test laboratory at BOSMAL Automotive Research and Development Institute, Poland to determine the deterioration in emission of gaseous (HC, CO, NO_x, CO₂) and solid (PM, PN) pollutants following the EU legislative test procedure (testing at 20°C to 30°C and at -7°C, performed over the NEDC). The tests revealed appreciable increases in emissions of regulated pollutants. Carbon dioxide emissions were some 11% to 15% greater, testifying to an increase in the quantity of injected fuel (12% to 16%). Modal analysis of diluted exhaust gas was also performed and cumulative emissions traces are presented. Using the modal results, the proportion emitted during the first segment of the test cycle (the elementary ECE cycle) was calculated for each pollutant. Results differed between the two test vehicles, by pollutant, and with the test temperature, taking values between 12% (for NO_x and CO₂) to 89% (for PN). Temperature data acquired during testing is also presented. Despite the excess emissions observed, the test vehicles compared relatively favorably to the results of similar tests conducted on other vehicles.

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INTRODUCTION

Compression ignition (CI; Diesel) engines are widely used in many automotive markets and are increasingly fitted to light-duty vehicles (passenger cars, PCs; sport-utility vehicles, SUVs; and light-commercial vehicles, LCVs), while CI engines are far and away the dominant engine type for heavy-duty vehicles the world over. The diesel engine is still the most fuel and thermodynamically efficient internal combustion engine type known, resulting in the best fuel economy and low CO₂ emissions, and is characterized by high specific torque, resulting in favorable drivability, as well as good durability. Direct injection diesel engines minimize the contribution to the greenhouse effect because their low fuel consumption leads to low CO₂ emissions. CI engines are not without their problems (namely emissions of NO_x and particulate matter - now legislated both as particle mass (PM), and particle number (PN), but significant progress has

been made in recent years regarding these issues (see e.g. [1-2]). The use of Diesel engines is continually increasing, even in passenger cars, although their popularity differs geographically. In the European Union (EU) (and Europe more generally), Diesel engines have a long and established history in light-duty applications (including in compact passenger cars with downsized engines) - in 2010, vehicles featuring Diesel engines accounted for 50.9% of new car sales in the EU and six EU member-states had penetrations rates in excess of 60% [3], although these figures have decreased somewhat since 2010. The proportion of passenger cars in the US market featuring CI engines has traditionally been very low, and any surges in popularity were short-lived. However, in recent years sales have increased somewhat, no doubt partly because of interest in obtaining greater fuel efficiency in light of recent fuel price increases. Additional factors include favorable performance (CI engines develop greater torque than gasoline vehicles, important for pulling

away in a heavy SUV or pickup, or when towing a heavy load), as well as high durability. From 2000 to 2007 the US market share of vehicles featuring CI engines doubled (from 2.3% to 4.6%). US popular interest in vehicles featuring CI engines is currently high by historical standards [4], even if this interest has not yet translated into a surge in sales. In light of the fact that Diesel engines are (or promise to be) in widespread use in many areas of the world, their impact on emissions of harmful compounds and greenhouse gases and air quality is significant. Investigations into the emissions performance of modern Diesel engines employed in light-duty applications are a global research priority. Since cold starts are demanding, emissions-intensive transient events [5,6], research on Diesel cold start emissions is an area particularly worthy of attention. While excess emissions associated with cold start have been investigated in great detail for spark ignition (SI) engines (reviewed in [5]), the cold start emissions behavior of CI engines has been subject to less attention, with some notable exceptions. Modern CI engines fundamentally differ from SI engines, both in terms of fuel delivery (namely direct injection) and fuel type (significantly lower volatility and higher viscosity than gasoline). However, some of the basic problems that affect SI engines at low temperatures also apply to CI engines, including high lubricating oil viscosity, fuel injection problems, the mass of the engine acting as a heatsink, sluggish kinetics and an overall low quality of combustion. Previous work has indicated that excess emissions from CI engines at low ambient temperatures are measurable and that substantial deteriorations in emissions of NO_x and particulate matter (PM) are often observed [e.g. 5,7,8]. Similarly, multiple studies have reported significant increases in fuel consumption (and CO_2 emissions) [e.g. 5,7,8]. Particularly for shorter journeys, the relative deterioration of fuel consumption may be greater than the relative deterioration suffered by SI engines [5]. Emissions from CI engines at low ambient temperatures are not currently subject to regulation in the EU, although certain US test procedures apply to all vehicles, including those featuring CI engines. In the EU, future emissions legislation will target NO_x emissions at low ambient temperatures [9], but other emissions may remain outside the scope of testing, at least for the next round of EU emissions legislation [10]. However, given the technical and legislative focus on real world emissions and moves in the direction of zero emissions, mandatory testing of CI engines at lower ambient temperatures is all but inevitable in the coming decades.

Cold start can be defined as when an engine is started with the temperatures of the oil, coolant and all elements of the engine (T) at the ambient temperature (T_a) [5]. During a hot start, T is equal (or very close to) the value of T observed during fully warmed-up operation (T_w). The term 'cool start' can be used for intermediate temperatures, where $T_a < T < T_w$ [5]. Due to humanity's socioeconomic habits and diurnal cycles, passenger cars experience a large number of cold and

cool starts. Similarly, vehicles employed in commercial applications will also often be started cold, or at least relatively cool. A soak time of a few hours is sufficient to allow the value of T to fall from T_w to very close to T_a . Cold and cool starts are challenging events for the engine, both from the hardware (engine) and software (calibration) points of view. This problem becomes progressively worse with reducing ambient temperature. In regions where T_a often falls below 0°C , a vehicle will frequently be exposed to very challenging start-up conditions.

During cold start of a CI engine, emission control is mainly concerned with UHC (unburned HC), CO and PM [5,7,8,11,12]. The main source of this emission is incomplete combustion due to delayed and retarded combustion or - in extreme cases - due to misfiring. The main option available to counteract these problems and maintain engine stability and drivability is excess fuelling [11,12]. The basic reason for undesirable harmful emissions is the low temperature that occurs during cold start followed by the initial phase of work, until the normal running temperature is reached. Additionally, before the exhaust gas aftertreatment system (Diesel oxidation catalyst, DOC) reaches its light-off temperature, its ability to oxidize HC and CO is very limited [11,12]. Emissions during cold start and engine warm-up are significant for overall emissions and the degree to which they dominate total trip emissions is a strong function of journey length (discussed in [5]; examined mathematically in [7,8]).

The origin and evolution of mandatory test procedures performed on vehicle featuring SI engines is outlined in [13]. Current EU legislation mandates testing at ambient temperature of -7°C for passenger cars featuring SI engines and that ambient temperature (inter alia) is widely used in studies examining cold start emissions. Additionally, the EU's Euro 6 standard will require a test at -7°C to demonstrate the functionality of the active NO_x aftertreatment system (the specific requirement is that the system reach its operating temperature within 400 s of start up, while operating over the UDC) [9]. In general, the anomaly that SI engines must be tested at -7°C while CI engines are exempt is under technical review by EU bodies [10]. It is recognized that Diesel emissions are higher at -7°C and the main pollutant of concern is NO_x [10]. Any future requirement that regulated emissions from CI vehicles featuring CI engines be tested at a reduced ambient temperature would likely specify -7°C as the ambient test temperature, at least in the EU. In light of these considerations, the experimental program described in this paper was conducted at two test temperatures: 25°C (being the midpoint of the 20°C to 30°C range specified in the legislation) and -7°C (for the aforementioned reasons). Results presented in this paper are a direct comparison of emissions results obtained at these two test temperatures.

Table 1. Current and future mooted low ambient temperature emissions limits for vehicles featuring CI engines in Europe and the USA

Legislation	Temp.	Cycle	HC	CO	NO _x
EU/SI vehicles (Euro 5)	-7°C	UDC	Yes	Yes	No
EU/CI vehicles (Euro 5)	None	None	No	No	No
EU/CI vehicles (Euro 6)	-7°C	UDC	No	No	Yes?
EU/CI vehicles (Euro 7?)	-7°C?	NEDC?	Yes?	Yes?	Yes?
USA/EPA	-6.7°C	FTP-75	No	Yes	No
California/CARB	10°C	Unified Cycle	Yes	Yes	Yes
California/CARB	-7°C	Unified Cycle	No	Yes	No
USA (Future)	-6.7°C?	?	No?	Yes	Yes?

The main factors that affect emissions and fuel consumption following cold start at low ambient temperatures are summarized graphically in Figure 1.

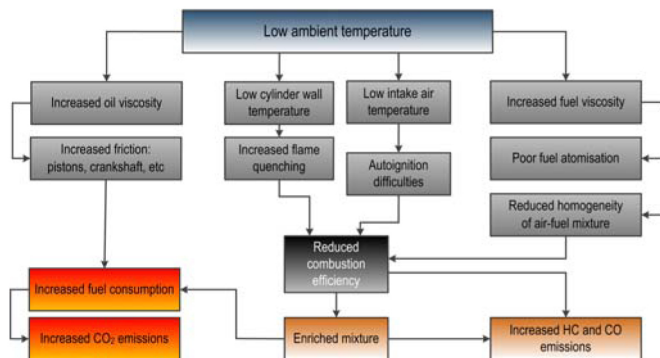


Figure 1. Cause-and-effect diagram of the fundamental difficulties of cold-start operation at low ambient temperatures [5]

When the absolute (Kelvin) scale is used, it becomes clear that an ambient temperature of -7°C (266K) is almost 11% 'colder' than +25°C (298K). During emissions testing, the vehicle is normally cooled by a cooling fan which blows air onto the engine and radiator at the same speed as the chassis dynamometer is rotating (proportional windspeed simulation). Therefore, even during the UDC, the engine is regularly cooled by a flow of air on the order of 5 m³/s; during the EUDC the flow is frequently on the order of 15 m³/s. According to Newton's law of cooling for the case of forced convection, the efficacy with which the cooling air can cool the radiator is a function of the difference in temperature between the two materials and thus it is logical to expect that cooling will be significantly more effective at -7°C. In terms of emissions, improved cooling can be desirable (e.g. reduced

NO_x emissions), but it is also viewed as a hindrance (e.g. slower warm-up, greater friction and fuel consumption) [5]. However, it is also reasonable to assume that increased fuel consumption might release more heat into the system and counteract the effect of lower ambient temperature (somewhat). Temperature data was collected from one of the test vehicles used in this study with the aim of gaining further insight into these effects.

In terms of commercial considerations, marketability and consumer satisfaction, cold starts and engine behavior at low and sub-zero ambient temperatures are also of significance. Exhaust emissions are of relatively little direct consequence to the vehicle's user in all but the most extreme cases. In contrast, fuel consumption is of great interest to the vehicle owner/operator and can easily be measured (nowadays even in real time). Tangible start-up difficulties, long warm-up times and impaired drivability are largely deemed unacceptable by modern drivers, at least where passenger cars are concerned.

EXPERIMENTAL

Test Laboratory and Emissions Measurements

All experimental work described in this paper was carried out in the Euro 5/6-compliant vehicle emissions testing laboratory at BOSMAL Automotive R&D Institute (Poland). This laboratory is housed within a climatic chamber with the capability of creating stable temperatures covering the temperature range -35°C to +60°C (Figure 2; see [14,15] for a detailed description of this test facility). The test vehicles were tested on a chassis dynamometer situated within the climatic chamber (Figure 3) [14]. A heated sampling line was connected to the test vehicles' tailpipe and the sample was conveyed to a constant volume sampler (CVS), for measurement of CO, CO₂ and NO_x, and through a dilution tunnel, for measurement of HC and particulate matter - both particle mass (PM) and particle number (PN), all in accordance with EU emissions test legislation for vehicles featuring CI engines. Using a CVS, diluted exhaust gas was collected in emissions sampling bags for analysis. Additionally, a modal analysis was also conducted on diluted exhaust emissions from the vehicles, in order to obtain transient emissions results. Non-gaseous emissions (PM and PN) were quantified according to the procedure specified in the legislation: a diluted sample of the exhaust gas was drawn through foil-backed Teflon filters to quantify PM; a condensation particle counter was used to measure particle number. Where the vehicles were tested at -7°C, the chassis dynamometer loading coefficients (F0, F1, F2) were each increased by 10%, as required by EU legislation. Each test was repeated three times and mean values taken for data analysis. Thermocouples were installed at multiple locations along the exhaust line of one of the test vehicles, with temperatures archived at a frequency of 1 Hz. The test

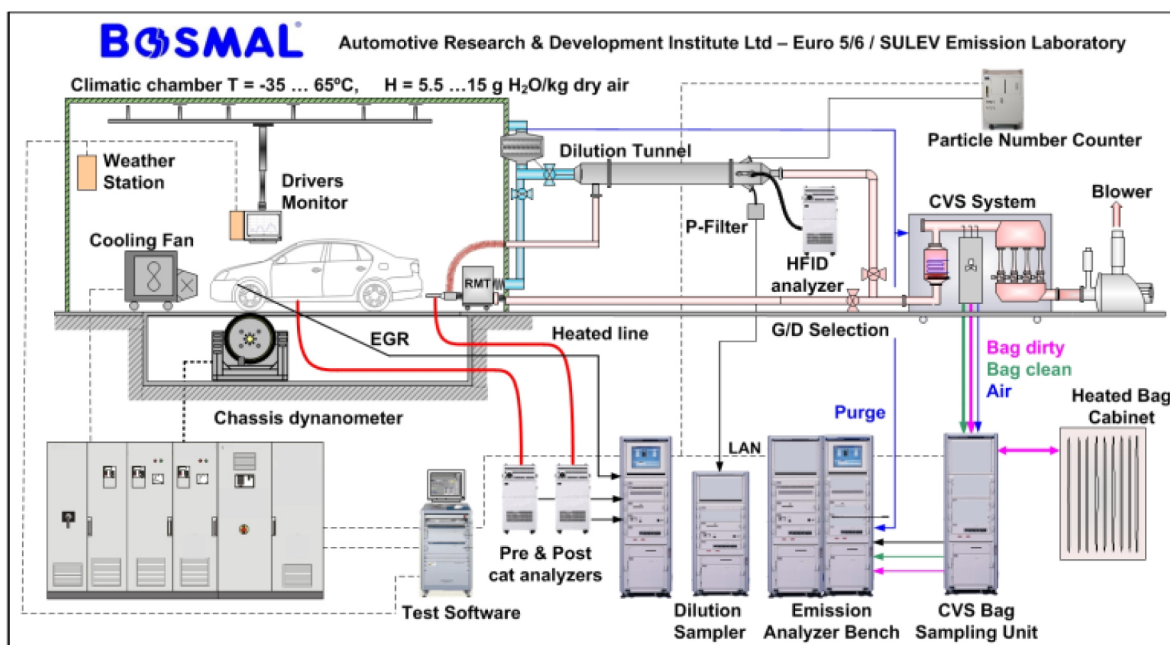


Figure 2. Schematic diagram of the emissions measurement setup, as used to measure emissions from the test vehicles

program described in this paper was performed as part of a broader ongoing test program evaluating the impact of low and sub-zero ambient temperatures on regulated and unregulated emissions from passenger cars and LCVs.



Figure 3. Exhaust emissions laboratory at BOSMAL, showing the chassis dynamometer, windspeed fan, drivers aid and a vehicle connected to the heated Diesel exhaust sampling line, all within the climatic chamber

Test Vehicles and Fuel

Two modern test vehicles were chosen for this study - vehicle 1 was a European LCV and vehicle 2 was a European PC. While vehicle 2 was designed for the carriage of light goods, the engine type is reasonably similar to some CI engines used in some mid-size pickup trucks and SUVs in other markets (including the USA). Both featured CI engines meeting the Euro 5b standard and were run-in and in perfect working order. The vehicles were commercially available models which had not been altered or modified in any way - except for the fact that vehicle 1 had four thermocouples to various points on the exhaust line. Both vehicles featured only standard starting aids (glow plugs). Key characteristics of the two test vehicles are shown in Table 2. A European Diesel fuel containing a nominal 5% FAME (i.e. B5) was used for all tests (see Table 3).

Table 2. Key characteristics of the two test vehicles

Parameter [units]	Vehicle 1	Vehicle 2
Vehicle type	LCV	PC
Inertia [kg]	2270	1360
Number of valves	16	16
Approx. displacement [dm ³]	3.0	1.6
Pre-cat aftertreatment system	Yes	No
Main aftertreatment system	DOC+DPF	DOC+DPF
Emissions standard	Euro 5b	Euro 5b
Mileage [km]	>5 000	>5 000
Thermocouples installed	Yes (four)	None