

Low Ambient Temperature Cold Start Emissions of Gaseous and Solid Pollutants from Euro 5 Vehicles featuring Direct and Indirect Injection Spark-Ignition Engines

Piotr Bielaczyc, Joseph Woodburn, and Andrzej Szczotka
BOSMAL Automotive R & D Institute Ltd.

ABSTRACT

Spark ignition (SI) engines are susceptible to excess emissions at low ambient temperatures. Direct injection leads to the formation of particulate matter (PM), and direct injection spark ignition (DISI) engines should show greater PM emissions at low ambient temperatures. This study compares excess emissions of gaseous and solid pollutants following cold start at a low ambient temperature and the standard test temperature. Euro 5 passenger cars were tested on a chassis dynamometer within BOSMAL's climate-controlled test chamber, according to European Union legislation (-7°C over the urban driving cycle (UDC), and at 25°C). Two vehicles were also tested over the entire New European Driving Cycle (NEDC). Emissions of regulated compounds and carbon dioxide were analyzed; particulate emissions (both mass and number) were also measured, all using standard procedures. Over the UDC, changes in emissions of hydrocarbons (HC), carbon monoxide (CO), and CO_2 were unequivocal; the situation for oxides of nitrogen (NO_x) was somewhat more complex. Over the entire NEDC, excess emissions were observed (though much larger for the UDC). The increase in CO_2 emissions over the entire NEDC was 17% for the MPI vehicle and 15% for the DISI vehicle. DISI particle number emissions increased by $\sim 50\%$; DISI particle mass by $>600\%$. A simple mathematical correction for the difference in ambient temperature was applied to the results. Excesses are greatest following start-up, but persist for hundreds of seconds. The temperature of the intake air had a measurable effect on certain emissions, even after the engine had been running for some time.

CITATION: Bielaczyc, P., Woodburn, J., and Szczotka, A., "Low Ambient Temperature Cold Start Emissions of Gaseous and Solid Pollutants from Euro 5 Vehicles featuring Direct and Indirect Injection Spark-Ignition Engines," *SAE Int. J. Fuels Lubr.* 6(3):2013, doi:10.4271/2013-24-0174.

INTRODUCTION

While Diesel engines have made significant advances in terms of penetration into the market for smaller engines, spark ignition engines running on gasoline remain the most common engine type employed in passenger cars in most markets the world over. One relatively recent development, however, is the growing popularity of vehicles featuring DISI engines. The market share for new vehicles featuring that engine type was estimated at just over 20% for the largest manufacturers in the EU for the year 2011 [1]. In 2011, two mainstream European manufacturers (BMW, VW) sold more vehicles with DISI engines than vehicles with MPI engines and one (Audi) appeared to sell virtually no vehicles with MPI engines at all [1]. The International Council on Clean Transportation even went so far as to call the increase seen in

the EU over the last decade "sharp" and "striking" [1]. Thus, emissions from DISI engines are an increasingly important topic for automotive emissions and air quality research.

In terms of emissions, cold starts are the most significant event experienced by a light-duty automotive SI engine [2]. Multiple physical processes are responsible for excess emissions during and following cold start, including ones relating to the engine oil (increased viscosity, increased friction), the low temperature of metal surfaces (flame quenching, condensation of liquid fuel) and the low temperature of the fuel and the intake air (mixture formation difficulties, reduced flame speeds) and an overall tendency for sluggish kinetics at lower temperatures, not least in the aftertreatment system (i.e. three-way catalyst, TWC), which is essentially inactive below a certain temperature (its light off temperature). In a different category, but no less

significant, is the requirement to use a rich mixture to achieve acceptable drivability as the engine warms up (see [2, 3, 4, 5] for recent reviews of these phenomena and their attendant emissions problems). While the term ‘emissions’ is generally used in discussions in this area, it is worth underlining that fuel consumption also increases significantly at lower ambient temperatures [2, 3, 4, 5].

The severity of the cold start emissions penalty generally increases with decreasing ambient temperature. The sole exception to this - under certain circumstances - is NO_x , formation of which is a strong function of in-cylinder temperature, and so emissions can be somewhat lower at lower ambient temperatures (briefly reviewed in [3]). This situation is widely recognized; legislation has been drafted by the EU, EPA and CARB in an attempt to limit this source of excess emissions (reviewed in [2,3]). In the EU, the Type VI test [6], conducted at an ambient temperature of -7°C , represents a legal means of controlling excess emissions at low ambient temperatures. At present, this test must be carried out on vehicles featuring MPI and DISI engines, but has not yet been extended to Diesels. EU legislation makes no distinction between vehicles featuring MPI and DISI engines with regard to gaseous emissions - however, PM (Euro 5) and PN (Euro 6) emissions are regulated from DISI engines only. When discussing regulated and unregulated pollutants in the context of cold start and low ambient temperatures, it is important to distinguish between regulated pollutants for the ‘standard’ Type I test (20°C to 30°C) and regulated pollutants for the Type VI test (-7°C), which at present are limited to HC and CO.

This paper reports experimental work conducted as part of a wide-ranging ongoing test program investigating cold start emissions and the influence of ambient temperature.

EXPERIMENTAL PROGRAMME

Test Facility & Analysers

The four experiments described here were carried out in the Euro 5/6-compliant vehicle emissions testing laboratory at BOSMAL Automotive R&D Institute (Poland), shown in [Figures 1 and 2](#) in the Appendix. This laboratory is housed within a climatic chamber with the capability of creating stable temperatures covering the range -35°C to $+60^\circ\text{C}$ (see [7,8] for a detailed description of this test facility). Vehicles were tested on a chassis dynamometer located within this climatic chamber ([Figure 2](#) in the Appendix). Two test temperatures were used: -7°C , as mandated for the Type VI test, and 25°C (being the midpoint of the 20°C - 30°C range permitted for execution of the Type I test). Emissions of HC, CO, NO_x and CO_2 were measured. All gaseous emissions were measured using a constant volume sampler and collecting a diluted sample of the exhaust in sampling bags. Emissions were calculated according to the EU legislative methodology [6]. Fuel consumption was calculated by means of the carbon balance method [6]. For the DISI vehicles,

particulate matter emissions were quantified using gravimetric and condensation particle counter methods. These methods involve passing the exhaust gas through a dilution tunnel, with characteristics in accordance with the demands of [6]. Particulate emissions from the MPI vehicles were not measured.

Experiments Performed

In the first experiment, a pool of MPI vehicles ($n=10$) and DISI vehicles ($n=3$) were tested over the UDC (Type VI test). Regulated emissions for the Type VI test (HC and CO) were measured and CO_2 was also measured to verify repeatability. Each vehicle was tested twice and the mean value taken.

In the second experiment, the same thirteen vehicles were tested over the UDC at -7°C and at 25°C , with all regulated emissions, CO_2 and fuel consumption (FC) measured in the same way. Particulate emissions were measured from the DISI vehicles, quantified by both mass (PM) and number (PN). Each vehicle was tested twice at each temperature and the mean value taken.

In the third experiment, an MPI passenger car and a DISI passenger car of similar swept volume and comparable unladen mass were tested over the NEDC at ambient temperatures of -7°C and 25°C . For both vehicles, HC, CO, NO_x and CO_2 were measured. For the DISI vehicle, particulate matter (PM) emissions were quantified using gravimetric and condensation particle counter methods, according to the relevant EU legislation. For this experiment, both vehicles were tested twice at 25°C and three times at -7°C and the mean values taken for further analysis.

In the fourth experiment, a different MPI vehicle and a different DISI vehicle were tested over the entire NEDC at -7°C and at 25°C . An attempt was made to correct the results obtained for the difference in ambient temperature. For this experiment, both vehicles were tested twice at 25°C and three times at -7°C and the mean values taken for further analysis (temperature correction).

Precisely the same base test procedure was used for testing of all cars at both ambient temperatures, except that when tested at -7°C the chassis dynamometer loading coefficients were all increased by 10% (for all vehicles), as stipulated in [6].

Test Vehicles

A total of 13 vehicles were tested, all of which were passenger cars which met the EU's Euro 5 emissions standard. Ten of the test vehicles' engines featured MPI fuel delivery systems; the remaining three vehicles featured DISI engines. The vehicles were all European passenger cars featuring the latest SI engine technology, of approximate displacement 1 dm^3 - 1.6 dm^3 . Most vehicles (including all three DISI vehicles) were turbocharged. All vehicles featured close-coupled TWCs. None of the DISI vehicles featured a dedicated particulate filter of any kind. No modifications whatsoever were made to the vehicles, in order to be

representative of the on-road passenger car fleet. The mileage range of all test vehicles was 5 000 km to 60 000 km.

Test Fuel

All vehicles were tested using the same fuel, a standard European gasoline whose key characteristics are presented in Table 1. This commercially available gasoline fulfilled the demands of the EN228:2009 standard.

Table 1. Key characteristics of the test fuel used in this study

Parameter [units]	Value
Research Octane Number [-]	95.3
Density [kg/dm ³]	0.7503
Benzene content [%v/v]	< 1.0
Aromatics [%v/v]	< 35
Olefins [%v/v]	< 18
Ethanol content [%v/v]	5.0
Sulfur content [mg/kg]	5.4

Driving Cycle

The well-known New European Driving Cycle (NEDC; see Figure 1) was used as the base cycle for this study. The first part of the cycle (the UDC) is used to perform a Type VI test and the entire cycle (UDC+EUDC) is used to perform a Type I test. Results from the UDC alone can be considered to loosely represent a 13-minute urban journey covering approximately 4 km.

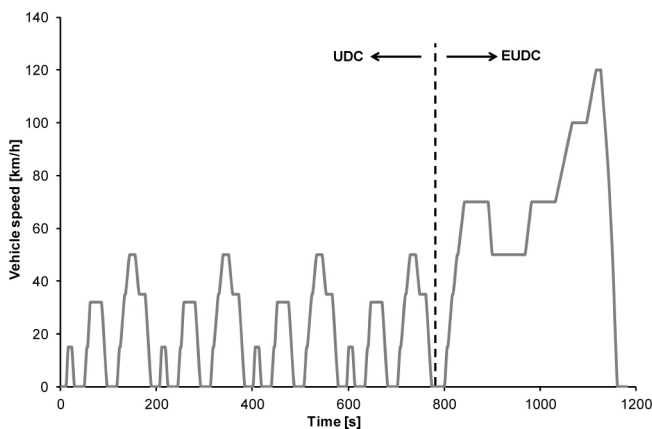


Figure 1. The New European Driving Cycle

RESULTS

When tested at 25°C, all test vehicles were found to meet the Euro 5 limits for the Type I test.

At 25°C, test to test repeatability was deemed acceptable for regulated emissions and very good for CO₂ and FC. Repeatability was somewhat lower for testing at -7°C, but was still within acceptable limits.

The results of the experiments conducted are presented in the following four subsections.

Emissions of CO and HC over the UDC at -7°C (Regulated Emissions for the Type VI Test)

When tested at -7°C according to the requirements of the Type VI test, all test vehicles met the HC and CO limits for that test type, in most cases by a relatively wide margin, as reported previously [2] and shown in Figure 2.

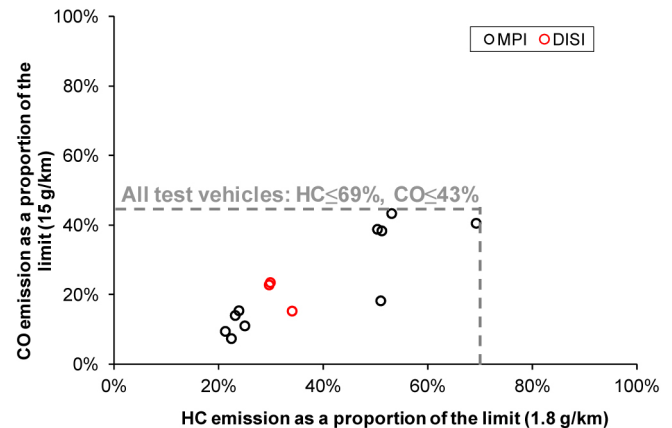


Figure 2. Regulated emissions (HC and CO) over the Type VI test for all test vehicles, presented as a proportion of the relevant emissions limit

There appeared to be no real difference between the MPI vehicles and the DISI vehicles - although the small population size for the DISI vehicles prevents the drawing of any firm conclusions. HC and CO emissions performance appeared not to correlate with engine swept volume. Significantly, five of the ten MPI vehicles had very low emissions (on the order of ~20% of the two emissions limits). Considering data from all thirteen test vehicles, it would appear that the HC limit is more stringent than the CO limit. If the HC limit were reduced by 30%, all vehicles tested here would still have emitted below the limit; if the CO limit were reduced by 55%, none of the test vehicles would exceed the new limit value. The fact that emissions were well below the Type VI test limits when tested at -7°C raises the interesting question of the ambient temperature at which each test vehicle would exactly meet the Type VI test limits. (This question will be addressed in forthcoming publications.)

Deterioration in Regulated Emissions and Fuel Consumption over the UDC at -7°C and at 25°C

Emissions results from the two test temperatures were compared by dividing the result obtained at -7°C by the result obtained at 25°C to give dimensionless deterioration factors [2,3]. These deterioration factors, rather than raw results, are discussed from this point onwards. A deterioration factor of 1.5 signifies a 50% increase in emissions (or fuel consumption) at the lower test temperatures a value of 0.9