

Particulate Emissions from European Vehicles Featuring Direct Injection Spark Ignition Engines Tested Under Laboratory Conditions

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ABSTRACT

Direct injection gasoline engines have been gaining popularity for passenger car applications, particularly in the EU. It is well known that emissions of particulate matter are an inherent disadvantage of spark ignition engine with direct injection. Direct injection of gasoline can lead to the formation of substantial numbers of particulates, a proportion of which survive to be emitted from the vehicle's exhaust. EU legislation limits particle mass (PM) emissions; particle number (PN) is soon to be limited, although an opt-out means that dedicated filters will not be required immediately. A range of tests were conducted on a pool of Euro 5 passenger cars in BOSMAL's climate controlled emissions laboratory, using EU legislative test methodology. In addition, further measurements were performed (particle size distribution, tests at multiple ambient temperatures). Results were compared to legislative limits and order of magnitude comparisons were made with emissions from indirect injection gasoline and direct injection Diesel engines. Size distribution profiles showed sensitivity both to the ambient temperature and to the thermal state of the engine (both during the test cycle and varying with the ambient temperature for the cold start). A substantial proportion of the total particles measured by the particle sizer were of too low a diameter to be detected by the current legislative PN method. In general, emissions from the test vehicles showed high number, small size and relatively low total mass. Preliminary results from a global harmonized test cycle are also presented, both for cold and hot start conditions. Given ongoing concern regarding the toxicity of very small particles and the upcoming particle number limits, research on this type of emission is a necessity for automotive exhaust emissions research.

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INTRODUCTION

Globally, spark ignition (SI) engines remain by far the most widely used engine type for light duty vehicles, a category which included passenger cars. Almost all of these vehicles feature internal combustion engines running on liquid fuel. Direct injection SI (DISI) engines have existed in various forms for many decades, but in recent years have markedly increased their market share in the USA and in the EU. The market share for new vehicles featuring that engine type was estimated at just over 20% for the largest manufacturers in the EU for 2011 [1] and the equivalent figure for the same year in the USA was 15% [2]. The increase in this proportion that has occurred in the EU over the last ten years has even been described as "striking" [1]. The EPA noted that the proportion had increased from around 0% to 15% in four years [2] - a rate of increase of almost 4% per annum. This growth rate lead the EPA to conclude that almost one car in every four sold in the USA in the year 2012 featured a DISI engine [2].

One of the main impacts of this trend relates to particulate emissions, which are always a key concern regarding DISI engines [3,4]. DISI engines offer multiple advantages over their PFI counterparts in terms of the potential for improved fuel efficiency, better control over the injection process and fuel dosing, and potential emissions benefits, for example during start up (examined in detail in [4]). However, an inherent disadvantage of DISI engines is their emission of particulate matter [4]. Such emissions occur as a result of the direct injection of petrol into the cylinder [5], and particle populations are generally (but not always) significantly greater than from port fuel injected (PFI) engines [3,4,5]. Since DISI engines and modern compression ignition (CI) engines share the key feature of direct injection, it is tempting to look for parallels between the two engine types for an explanation of the 'Diesel-like' particulate emissions from DISI engines. While there are indeed some similarities, there are also important differences in terms of the timing and nature of the two combustion processes [3], with resulting impacts on particulate emissions. One aspect which may be of considerable importance is that of particulate emissions from slow burning

pool fires, which can form on the wetted cylinder head and wall (discussed in [3,5] and examined in [4]). The massive difference in the volatility of gasoline and Diesel cause droplets of those substances to behave differently, with implications for a variety of particulate-forming processes, not least of which are gas-to-solid reactions [3]. Furthermore, the elimination on particulates within the vehicle's powertrain also affects exhaust emissions. While in-cylinder oxidation can reduce the population of particulates substantially [3], the extent to which this occurs and the nature and timing of the reaction are somewhat different in DISI engines and Diesel engines [3]. Finally, the elimination of particulates in the aftertreatment system is obviously very different: oxidation of particulates can occur in both TWCs and DOCs, but these application-specific devices behave differently, and have different levels of available oxygen. On top of that, the fact that modern CI vehicles feature Diesel particulate filters (DPFs), while gasoline particulate filters (GPFs) have yet to be widely adopted is also of great importance in any comparison (quantitative or qualitative) of particulate emissions from DISI and CI engines. In any case, engine out emissions from DISI engines are normally 1-2 orders of magnitude below engine out emissions from CI engines [5].

The European Union has acted on various scientific recommendations by setting limits for solid emissions from vehicles featuring DISI engines. In the US, the EPA and CARB have made similar moves, and Japan followed. A summary of these legislative limits is presented in Table 1. At the time of writing, no other legislative authority had set any limits for PN emissions from passenger cars featuring DISI engines, although a few countries had unilaterally adopted US or EU limits. Note that the values presented in Table 1 are emissions *limits*, and that not all of these limits are directly comparable, since different test cycles are quantification procedures are used for testing in the four jurisdictions, as shown in the fourth column of the table.

Table 1. Summary of EU legislation limiting particulate emissions for passenger cars featuring DISI engines

Jurisdiction / legislative stage	PM [mg/km] *	PN [# /km]	Applicable test cycle
EU / Euro 5a	5.0	-	NEDC
EU / Euro 5b	4.5	-	NEDC
EU / Euro 6b	4.5	Effectively 6.0×10^{12} **	NEDC
EU / Euro 6c	4.5	6.0×10^{11}	NEDC? WLTC?
EPA / Tier II ("full useful life", 8 bins)	0.0 - 12.43	None	FTP-75
CARB / Exhaust Mass Emission Standards (2015)	6.21	None	FTP-75
CARB / Particulate Standards (2017-)	1.86	None	FTP-75
CARB / Particulate Standards (2027-)	0.62	None (?)	FTP-75
Japan / Post New Long Term	5.0	None	JC08

* Limits set in [g/mile] (EPA/CARB) have been converted to [mg/km]

** EU regulation No 459/2012 contains the following text: "...upon the choice of the manufacturer, a particle number emission limit of 6×10^{12} #/km shall apply to vehicles with a direct injection positive ignition engine"

Now that the EU has set relatively strict particle mass and number limits for vehicles with CI engines which necessitate the use of a dedicated Diesel particulate filter (DPF), increasing attention is turning to other automotive sources of exhaust particulate (c.f. [5,6]). In this context, the growing popularity of vehicles featuring DISI engines is highly significant. Furthermore, the physicochemical characteristics of the particles themselves are of great importance regarding air quality impacts and potential impacts on human health; the size of the particles may be the most important parameter, with harmfulness increasing as diameter decreases [7].

Traditionally, particulate emissions have been quantified in terms of mass (units [g/km] or [mg/km]), with a move towards particle number emissions (units [# /km]) in recent years, in line with the changes taking place in EU legislation. However, systems are available which measure the size distribution of solid particles in the exhaust. Despite not being directly subject to legislative limits in any jurisdiction, particle size is potentially of legal importance in terms of the relative contribution to various size fractions of ambient PM. Particle size distribution profiles are also instrumental in determining (or at least estimating) the toxicological impacts of particles. Finally, particle characteristics can be indicative of the particle formation processes within the cylinders and the response to changes in engine operating parameters, as best exemplified under transient driving conditions. Other methods are also available, such as measurement of exhaust gas opacity (units [%], among others) and instantaneous measurements of the mass concentration of particles in the exhaust gas (units e.g. [mg/m³]). See [8] for a practical discussion of the sampling and measurement of solid particulates in vehicle exhaust; see [9] for an overview of instrumentation for measuring soot emissions.

The experimental work described in this paper used three techniques to quantify emissions of particulate matter from vehicles featuring DISI engines: gravimetric (PM filter), number (PN), and size resolved number ('sizer'), which are commented upon in the following section.

EXPERIMENTAL

Test Laboratory & Particulate Matter Quantification Systems

All experimental work reported in this paper was conducted in the Euro 5/6-compliant vehicle emissions testing laboratory at BOSMAL Automotive R&D Institute (Poland). The laboratory is shown in Figures A1 and A2 in the Appendix. This laboratory is located within a climatic chamber with the capability of creating stable temperatures covering the range -35°C to +60°C. (The laboratory has been described in detail elsewhere [10,11].) All equipment for the sampling, transfer, conditioning and measurement of particulate matter is fully PMP-compliant. (See Figure A3 in the Appendix for a general schematic of the PN sampling system.) All test vehicles were tested on a chassis dynamometer which is situated within this climatic chamber.

(refer to [Figure A2](#) in the Appendix). The temperatures used for legislative testing in the EU (+25°C, - 7°C) were set, depending on the test in question. Emissions of gaseous pollutants and CO₂ were measured in accordance with EU legislation [12]. These emission results were only used for verification purposes and their measurement can be considered to have no influence whatsoever on the results obtained for particulate matter.

The subject of this study - particulate matter emissions - were quantified using gravimetric and condensation particle counter methods, in accordance with [12]; see also [Figure A3](#) in the Appendix. These methods involve passing the exhaust gas through a dilution tunnel, with characteristics in accordance with the demands of the applicable sections of [12].

For PN quantification, the particle number counting system used was a Horiba MEXA-2000SPCS, which features a TSI 3970 CPC. This CPC can measure particle concentrations in the range 0-50 000 #/cm³, but in order to comply with [12], the dilution settings must be chosen such that the maximum particle concentration does not exceed 10 000 #/cm³. The required dilution ratio varies from vehicle to vehicle, but the lowest value is 1:150 and the highest 1:3000. For each vehicle tested here, the lowest possible dilution was used, while maintaining the maximum measured particle concentration at a level well below 10 000 #/cm³.

For PM sampling, the flowrate of the sample passing through the filters was 100 liters/minute for all tests.

It is important to note that according to EU legislation, the sample fed into the CPC originates in the dilution tunnel and is further diluted with hot air by special systems within that device, whereas the sample passed through the filters is taken directly from the dilution tunnel without any further dilution.

For the experiments which used the particle size classifier, (TSI 3090 EEPS - Exhaust Emissions Particle Sizer™, see [13] for a detailed description) the sample fed to that device was taken from a point in the dilution tunnel very close to the CPC's sampling point, using an identical coniform sampling probe to that used by the CPC, and a heated sampling line. The connections between the dilution tunnel and the CPC and the EEPS are shown in [Figure A1](#) in the Appendix, together with the connection from the vehicle's exhaust to the dilution tunnel. The EEPS has a different particle detection method and is capable of handling higher concentrations of particulate in the sample gas; its internal dilution ratio is significantly lower than that of the CPC. The EEPS is designed for research activities and is not specified as essential equipment for any legislative measurement; the sample handling procedures of the CPC and EEPS are not fully comparable. Notwithstanding those differences, both devices took their samples from adjacent locations on the dilution tunnel, within which the flow is highly homogenized, with a high characteristic Reynolds number.

Experiments Performed

For the first experiment, a pool of European vehicles (n=6; with one vehicle tested on two different fuels), including two DISI vehicles were tested over the NEDC (Type I test), in accordance with European legislation. Exhaust particulate emissions were quantified in terms of mass (PM) and number (PN). Each vehicle was tested twice and the mean values taken. While vehicles featuring DISI engines are the subject of this paper, the other vehicles were tested using an identical test procedure in order to obtain information on where DISI vehicles' particulate emissions lie in relation to emissions from PFI and CI vehicles. While PFI vehicles have no specified legislative test methodology for measuring PM emissions, the legislative method for DISI and CI vehicles was employed, in order to permit direct comparisons of the results to be made.

In the second experiment, two European DISI vehicles were tested over the NEDC in precisely the same manner as the first experiment. However, the tests were later repeated at an ambient temperature of -7°C. Three tests were performed on each vehicle (at each test temperature) and the mean values taken.

In the third experiment, two DISI vehicles were tested over the NEDC at +25°C and at -7°C. For these experiments, PN emissions were measured using the CPC and the EEPS was used to obtain size resolved particle number counts. PM emissions were not measured.

In the fourth experiment, a single DISI vehicle was subjected to 14 repeat tests. Between each pair of emissions tests, the vehicle underwent mileage accumulation on the road, under a wide range of atmospheric and vehicle usage conditions. EU legislative test procedures were employed to measure PM and PN. During the course of the research program the vehicle accumulated approximately 40 000 km mileage. Results were compared to Euro 6 limits.

Test Vehicles

The subject of this study were European passenger cars featuring DISI engines. Several such vehicles were tested (vehicles 1, 2, 7, 8, 9 and 10), all of which were unmodified vehicles with mileages between 12 000 km and 100 000 km. All these DISI engines used the stoichiometric combustion strategy ('λ1') and were turbocharged. The vehicles had representative European displacements of 1.4 dm³-1.8 dm³. In addition, two PFI vehicles (vehicles 3 and 4) and two CI vehicles (vehicles 5 and 6) were also tested in the course of experiment 1. These vehicles also met the Euro 5 standard and were similarly unmodified and had mileages greater than 10 000 km. Displacements of the PFI and CI engines ranged from 1.2 dm³-1.9 dm³. In terms of key differences from the DISI test vehicles, the CI vehicles featured DPFs and the PFI vehicles were naturally aspirated. One of the PFI vehicles (vehicle 4) was a bi-fuel vehicle, which was tested on both gasoline and CNG. Selected key characteristics of the test vehicles are shown in [Table 2](#).

Table 2. Key characteristics of the test vehicles used in this study

Vehicle	Engine type	Fuel delivery	Approx. disp. [dm ³]	Inertia (test mass) [kg]	Aftertreatment system	Used in Experiment
1	SI	DI	1.4	1360	TWC, close-coupled	1
2	SI	DI	1.8	1360	TWC, close-coupled	1
3	SI	PFI	1.2	1020	TWC, close-coupled	1
4	SI, bi-fuel	PFI	1.4	1130	TWC, close-coupled	1
5	CI	DI	1.3	1250	DOC+DPF, close-coupled	1
6	CI	DI	1.9	1470	DOC+DPF, close-coupled	1
7	SI	DI	1.4	1360	TWC, close-coupled	2
8	SI	DI	1.6	1360	TWC, close-coupled	3
9	SI	DI	1.6	1700	TWC, close-coupled	3
10	SI	DI	1.8	1700	TWC, close-coupled	4

Test Fuel

All SI vehicles were tested using the same fuel, a typical European gasoline whose key characteristics are presented in Table 3. This gasoline fulfilled the demands of the EN228:2009 standard. The Diesel and CNG fuels for certain vehicles were also of European origin and were standard, commercially-available fuels fulfilling all EU criteria for those fuel types.

Table 3. Key characteristics of the test fuel used in this study

Parameter [units]	Value
Research Octane Number [-]	95.3
Density [kg/dm ³]	0.7506
Benzene content [%v/v]	< 1.0
Aromatics [%v/v]	< 35
Olefins [%v/v]	< 18
Ethanol content [%v/v]	5.0
Sulfur content [mg/kg]	5.2

Driving Cycle

The current European legislative cycle, known as the New European Driving Cycle (NEDC; see Figure 1) was used as the base cycle for this study. Results from the UDC alone can be considered to loosely represent a 13-minute urban journey

covering approximately 4 km. Results from the EUDC can be considered to represent a short highway trip covering approximately 7 km and commenced when the engine has been running for 13 minutes. This driving cycle was also used to precondition the vehicles (followed by a soak time of at least 12 hours); see [12] for full details on the test cycle and vehicle preconditioning and heat soaking procedures.

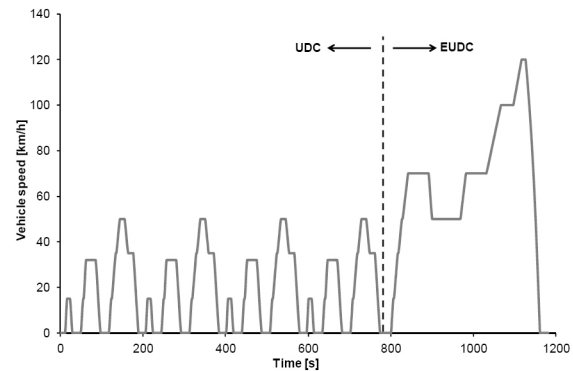


Figure 1. The New European Driving Cycle

RESULTS

Experiment 1: Comparison of DISI Emissions to PFI and CI Emissions

Results from the pool of vehicles tested in experiment 1 are shown in Figures 2 and 3.

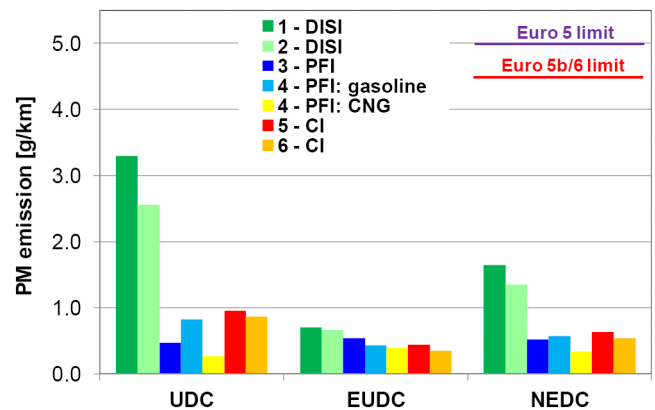


Figure 2. PM emissions from the vehicles tested in experiment 1

All vehicles met the Euro 5 and Euro 5b/6 PM emissions limits. PM emissions from the two DISI vehicles were considerably higher than the PFI vehicles during the UDC phase, but only somewhat higher during the EUDC phase. SI engines require a prolonged period of enrichment following cold start, even at an ambient temperature of +25°C; enriched mixtures are known to increase formation of particulates in DISI engines [14]. The CI engines tested here all met the Euro 5 standard, and so all featured DPFs - for this reason, their PM emissions were very low, being even lower than from the PFI vehicles.