

The Impact of Fuel Ethanol Content on Particulate Emissions from Light-Duty Vehicles Featuring Spark Ignition Engines

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ABSTRACT

Ethanol has long been a fuel of considerable interest for use as an automotive fuel in spark ignition (SI) internal combustion engines. In recent years, concerns over oil supplies, sustainability and geopolitical factors have lead multiple jurisdictions to mandate the blending of ethanol into standard gasoline. The impact of blend ethanol content on gaseous emissions has been widely studied; particulate matter emissions have received somewhat less attention, despite these emissions being regulated in the USA. Currently, in the EU particulate matter emissions from SI engines are partially regulated - only vehicles featuring direct injection SI engines are subject to emissions limits. A range of experiments was conducted to determine the impact of fuel ethanol content on the emissions of solid pollutants from Euro 5 passenger cars. All testing was conducted in BOSMAL's climate-controlled test facility, with tests performed at multiple ambient temperatures, including the two temperatures specified in EU legislation (+25°C, -7°C). Gravimetric (filter) and particle counting methods were used to quantify emissions, as well as particle size distribution profiles. A range of vehicles were tested, featuring both direct injection and port fuel injection SI engines. Where applicable, all testing was carried out in accordance with the demands of EU regulations; the New European Driving Cycle was used for all tests. Overall, results indicated the impact of ethanol content on exhaust emissions of particle mass to be relatively modest. Particle number and size distribution showed somewhat greater sensitivity to fuel ethanol content, highlighting their utility as research metrics. The implications of these observations and increasing pressure to switch to more sustainable energy sources for automotive propulsion are discussed.

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INTRODUCTION

Notwithstanding the various strengths of the Diesel engine for light duty applications and the soaring popularity of that engine type in the European market, on a global scale spark ignition (SI) engines remain by far the most widely used engine type for light duty vehicles. Exhaust emissions from SI engines range from very well known, regulated emissions (such as HC and CO) to lesser known, unregulated emissions such as NH₃ and N₂O. Sitting between these two groups, particulate emissions from SI engines can be considered to be *partially regulated*. Self evidently, particulate emissions are not gaseous emissions, but in fact they form part of the wide range of hazardous and toxic substances emitted in the exhaust of vehicles featuring SI engines and they are normally covered in the same legislation setting limits for gaseous pollutants.

However, since particulate emissions from SI engines are generally much lower than emissions from Diesel engines, SI particulate emissions have long been ignored. Towards the end of the 1990s, renewed interest in direct injection spark ignition

(DISI) engines (which have much higher particulate emissions than 'standard' port fuel injected SI engines) brought the issue of particulate emissions from SI engines to the attention of the automotive testing community. (The reader is directed to [1, 2] for two widely-cited papers from that era, the latter being a wide-ranging discussion of DISI engines, including their particulate emissions.) [3, 4] represent more recent, comprehensive reviews of the topic in general.

This concern over particulate emissions eventually translated into legislation aimed at curbing such emissions. In the EU, legislation was introduced limiting the PM emissions from vehicles featuring DISI engines (see [3] for a discussion), and a PN limit has been confirmed, but has not yet entered into force [5]. The Euro 6 PN limit includes a phase-in, during which emissions ten times higher than the equivalent Diesel limit will be deemed acceptable [5]. After this phase-in period, a limit of 6.0×10¹¹ #/km will apply [5]. Outside the EU, EPA, CARB and the Japanese authorities have also set PM limits, albeit with the main focus generally on emissions from Diesel engines.

Concurrent to this increased concern over particulate emissions, there has been a move towards the usage of ethanol as an extender for standard gasoline. The usage of ethanol as a fuel for SI engines has a long history, but in recent years the idea has increased in appeal due to the potential of ethanol fuel to reduce lifecycle greenhouse gas emissions. Ethanol blends can be created by splash blending ethanol into gasoline, usually identified as E5, E10, etc (according to the volumetric proportion of ethanol in the blend). The E85 blend is the highest commonly used ethanol blend, but such a fuel type is only suitable for usage in flexible fuel vehicles (FFVs).

The majority of all research published on the emissions impact of using ethanol blends in SI engines has focused on regulated emissions [6, 7], with a smaller number covering unregulated gaseous emissions, hydrocarbon speciation, etc [8]. However, some authors have examined the impact of ethanol blends on particulate emissions: see [9] for a brief graphical review; see [8],[10],[11],[12] for examples of recent research which has included discussions of this topic, and see [13] for metadata on particulate emissions from FFVs operating on E85.

The overall consensus in the literature is that particulate matter emissions generally decrease somewhat as blend ethanol content is raised [9],[11]. There are, however, some caveats: this trend is not always observed (in fact, the opposite has been reported [9],[12],[14]); the test method and sampling conditions can have a strong impact on the results; the rather loose definition of what constitutes “particulates” and how they should be sampled can complicate inter-study comparisons. Certain particulate quantification methods are not sensitive enough to distinguish particulate emissions at very low levels, thereby failing to reveal any meaningful impact of the addition of ethanol [8]. More sophisticated measurement techniques such as particle number count and instantaneous particle size distribution curves can be better indicators of differences in particle formation and emission processes occurring as a result of the fuel ethanol level [9].

There are a range of reasons why the addition of ethanol to gasoline might affect particulate matter emissions. The physicochemical properties of ethanol alter the properties of blends to which it is added in terms of characteristics such as density, viscosity, heat capacity, boiling curve, etc [7],[8]. In turn, these fuel properties have strong controlling effects on injection behavior, combustion temperatures, etc, all of which could potentially influence the rate of formation of particulate matter. The presence of an oxygen atom within the ethanol molecule is an important difference [6],[7] (standard E0 gasoline contains no oxygenated species), and the presence of oxygen atoms within droplets of uncombusted fuel in the cylinder is sure to have an impact - however slight - on the formation of particulate matter. Furthermore, there are two processes which can affect particulate matter exhaust emissions, both of which can be affected by fuel chemistry: in-cylinder destruction (oxidation) of particulates and oxidization in the aftertreatment system (TWC).

Some fundamental SI engine particle formation research has focused on engine out emissions (no aftertreatment) [10],[11], while other studies have measured tailpipe emissions [8],[15]; Peckham et al. [16] measured emissions at both locations.

The aim of this paper was to contribute to the existing literature on this subject by presenting results obtained from a test program performed using latest technology European vehicles, featuring both PFI and DISI engines. The work described and reported on in this paper represents a continuation of previous ethanol-gasoline blend emissions research by the authors [6],[7],[8], but with a specific focus on particulate emissions.

EXPERIMENTAL PROGRAM

An experimental program was carried out to obtain particulate emissions data based on three key metrics: particle mass (gravimetric method - sample collected on filters), particle number (particle counting method - sample passed through a CPC) and particle size distribution (size-selective particle counting - sample passed through EEPS). A detailed description of the EEPS system can be found in [17]; a detailed specification of PMP-compliant CPC systems and apparatus for performing gravimetric (filter) measurements can be found in [18]. The approaches used to obtain data on these three metrics are outlined below, together with details of the test facility, test vehicles, test cycle and fuel blends employed.

The four experiments described here were all carried out in the Euro 5/6-compliant vehicle emissions testing laboratory at BOSMAL Automotive R&D Institute (Poland), shown in [Figures A1 and A2](#) in the [Appendix](#). This laboratory is housed within a climatic chamber with the capability of creating stable temperatures covering the range -35°C to $+60^{\circ}\text{C}$ ([19],[20] present detailed descriptions of this test facility). Vehicles were tested on a chassis dynamometer located within this climatic chamber ([Figure A2](#) in the [Appendix](#)). In total three test temperatures were used: $+25^{\circ}\text{C}$, -7°C (the two temperatures used for legislative testing in the EU), and -15°C . Emissions of regulated gaseous pollutants and CO_2 were measured to monitor test-to-test repeatability. 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 the applicable sections of [18]. All gravimetric filter measurements were performed in accordance with the methodology mandated in [18], with one crucial difference: in order to have one result per phase, rather than one result per test, one filter was used for each phase of the cycle, rather than a single filter for the entire test. The CVS was set so that the mean dilution ratio during the test was within the range 15:1 to 25:1 (note that this meant using different flow rates for different vehicles). The flow rate across the filters was 100 liters/minute in all tests. For the experiments which used the particle size classifier, the sample fed to that device was taken from a point in the dilution tunnel very close to the CPC sampling point, using an identical conformal sampling probe, as described in [18]. Preliminary testing

showed that the enabling or disabling of sampling of diluted exhaust gas by the gravimetric, CPC and EEPS systems had no detectable impact on the results obtained by the other systems. The connections between the CPC and the EEPS are shown in [Figure A1](#) in the [Appendix](#), along with the connection from the vehicle's exhaust to the dilution tunnel.

Experiments Performed

In the first experiment, a vehicle featuring a PFI engine (vehicle 1) was tested on three ethanol blends: E10, E25 and E50, all tested under identical test conditions at 25°C. During these tests, particle mass and particle number were quantified according to the EU legislative procedure (although technically vehicle 1 did not have a specified methodology). Four tests were performed on each blend and the mean values were plotted.

In the second experiment, another vehicle featuring a PFI engine (vehicle 2) was tested on two ethanol blends: E5 and E50, both tested under identical test conditions at 25°C. During these tests, particle number was measured using the CPC and particle size distributions were *simultaneously* measured using the EEPS system. Two tests were performed on each blend and the mean value was taken for further analysis, which included a comparison of the results obtained from the CPC and from the EEPS.

In the third experiment, a vehicle featuring a PFI engine (vehicle 3) and a vehicle featuring a DISI engine (vehicle 4) were tested on multiple ethanol blends (E5, E10, E25 and E50 - covering an order of magnitude of ethanol content) at an ambient temperature of 25°C. Particle mass and particle number were quantified according to the legislative procedure. Three to four tests were performed on each blend to obtain a reliable mean value for analysis of the results.

In the fourth experiment, two vehicles featuring DISI engines (vehicles 5 and 6) were tested on multiple ethanol blends at two sub-zero ambient test temperatures (-7°C and -15°C). Vehicle 5 was an FFV, which was tested on blends E0, E10, E20 and E85. Vehicle 6 was a non-FFV, which was tested on blends E0, E10 and E20. Particle mass and particle number were quantified according to the legislative procedure. A total of three tests were performed on each blend to obtain a reliable mean value for analysis of the results. Relative results from this experiment are presented in comparison to results obtained on the E0 fuel.

Notwithstanding the particulars of the various experiments detailed earlier in this section, precisely the same base test procedure was used for testing of all vehicles at all ambient temperatures, except for all tests conducted at -7°C and -15°C, where the chassis dynamometer loading coefficients were all increased by 10%. This modification to the chassis dynamometer loading is mandated in [18].

Test Vehicles

A total of six vehicles were tested, all of which met the EU's Euro 5 emissions standard. Vehicles 1-3 featured indirect injection PFI fuel delivery systems; vehicles 4-6 featured stoichiometric ('λ1') DISI engines. The vehicles were all European passenger cars featuring the latest SI engine technology, of approximate swept volume 1.2 dm³ - 1.6 dm³. All three PFI vehicles were naturally aspirated; all three DISI vehicles were turbocharged. All vehicles featured close-coupled TWCs, but 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 as representative of passenger car fleet as possible. The mileage range of all test vehicles was 15 000 km to 40 000 km.

Some basic information relating to the test vehicles, together with brief details of the experiments performed on each vehicle, are presented in [Table 1](#).

Table 1. Basic details of the test vehicles, experiments and particulate measuring equipment employed in this study

Vehicle number	1	2	3	4	5	6
Fuel delivery system type	PFI	PFI	PFI	DISI	DISI, FFV	DISI
Approx. swept volume [dm ³]	1.4	1.2	1.4	1.4	1.6	1.6
Used in Experiment(s)	1	2	3	1	4	4
Tested on blends	E10, E25, E50	E5, E50	E5, E10, E25, E50	E5, E10, E25, E50	E0, E10, E20, E85	E0, E10, E20
Tested at temperatures [°C]	+25	+25	+25	+25	-7°C, -15°C	-7°C, -15°C
Tested using	Filters, CPC	CPC, EEPS	Filters, CPC	Filters, CPC	Filters, CPC	Filters, CPC

Test Fuel Blends

Three base fuels were used in this study: a base gasoline fuel containing 5% ethanol (E5) a base gasoline fuel containing no ethanol (E0) and a blend containing 85% ethanol by volume (E85). The E0 fuel was only used 'raw', whereas the E5 and E85 fuels were both used 'raw' and were also used to create blends E10, E20, E25 and E50 through splash blending. The E5 fuel can be considered the base fuel for the experimental work described in this paper; the key characteristics of that fuel are shown in [Table 2](#). A full physicochemical analysis was conducted on most of the gasoline-ethanol blends employed in this study. The results are presented in [Table A1](#) in the [Appendix](#).

Table 2. Key characteristics of the E5 fuel used in this study

Parameter [units]	Value
Research Octane Number [-]	95.2
Density [kg/dm ³]	0.7492
Benzene content [%v/v]	< 1.0
Aromatics [%v/v]	< 35
Olefins [%v/v]	< 18
Ethanol content [%v/v]	5.0
Sulfur content [mg/kg]	5.1

Driving Cycle

All testing described here were obtained over the well-known New European Driving Cycle (NEDC; see Figure 1 and [18]). The first part of the cycle (the UDC) involves a cold start at the ambient temperature and is followed by the second EUDC phase. The entire cycle lasts 1180 seconds and covers a distance of just over 11 km. Results from the UDC alone can be considered to loosely represent a 13-minute urban journey covering approximately 4 km, which - crucially - includes a cold start at whichever ambient temperature is used for testing.

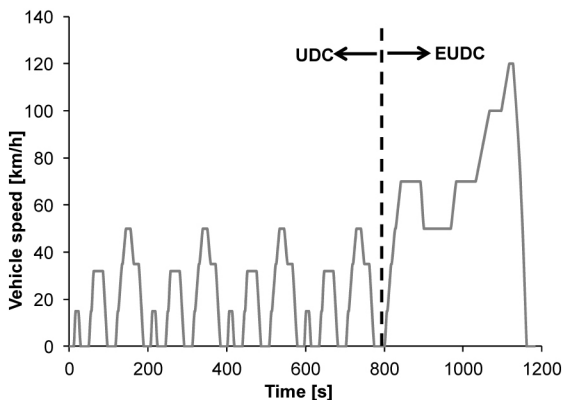


Figure 1. The New European Driving Cycle

RESULTS AND DISCUSSION

Particulate matter was detected in the exhaust of all vehicles for all fuel blends. All three particulate quantification methods employed generated results which were deemed plausible, with levels of test-to-test variability deemed generally acceptable for the relatively low emissions levels for Euro 5 light duty vehicles of small-to-modest displacement ($\leq 1.6 \text{ dm}^3$).

Experiment 1

Results from vehicle 1 are presented in Figures 2, 3.

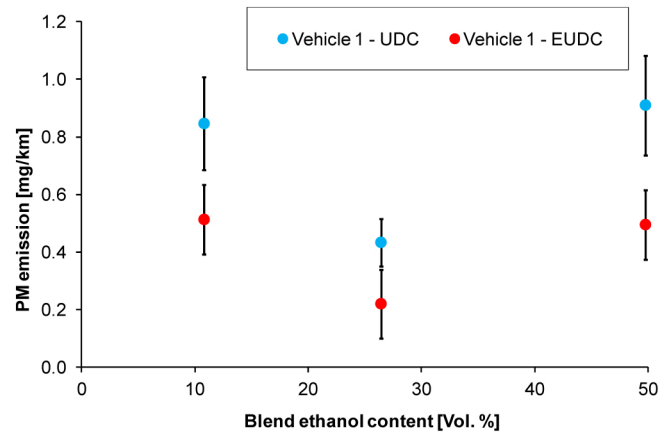


Figure 2. PM results for the UDC and EUDC phases of the NEDC for vehicle 1 running on the three test blends. The error bars show the calculated standard error for each datapoint ($n=4$)

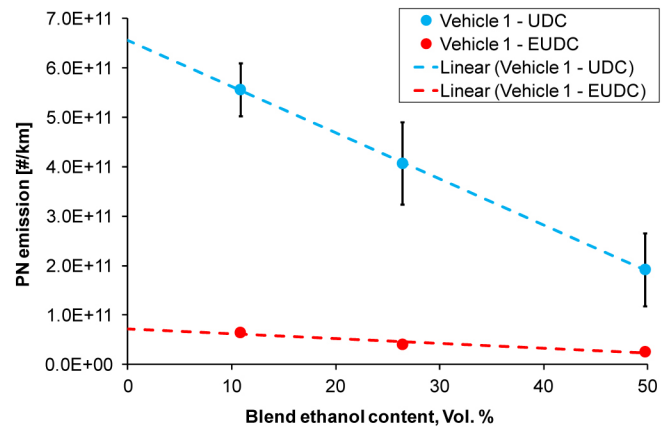


Figure 3. PN results for the UDC and EUDC phases of the NEDC for vehicle 1 running on the three test blends. Linear trendlines have been fitted to the datapoints ($R^2 > 0.98$ in both cases); the error bars show the calculated standard error for each datapoint ($n=4$); error values for the EUDC are non-zero, but small enough not to be visible on the graph

Regarding PM measurements results were roughly 100% higher for the UDC than for the EUDC; for PN results from the UDC were 741% to 1002% higher than over the EUDC, depending on the blend. Overall, emissions from vehicle 1 were relatively low. All PM results were below 1 mg/km (Figure 2), a similar range to that reported for PFI vehicles elsewhere (cf. [8],[15],[21]). PM emissions were higher for the UDC than the EUDC for all three blends, but the results failed to show a clear, linear relationship between blend ethanol content and PM emissions. Although there are only three datapoints on the PN plot (Figure 3), the results appeared to indicate a linear relationship, for both the UDC and the EUDC. These results could be verified by testing other blends (e.g. E0, E20, E40) on the same test vehicle, and seeing how closely the results fall to the trendlines shown here.

The lowest PM emissions were observed when the vehicle was running on the E25 blend, but this trend was sharply reversed when the ethanol content was raised to 50%; results from the