

Strategies Towards Meeting Future Particulate Matter Emission Requirements in Homogeneous Gasoline Direct Injection Engines

2011-01-1212

Published
04/12/2011

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doi:[10.4271/2011-01-1212](https://doi.org/10.4271/2011-01-1212)

ABSTRACT

Since the introduction of the EURO 5 emission legislation particulate matter emissions are no longer only a concern in the development of Diesel engine powertrains. In addition to particulate mass (PM) requirements the new European legislation will also foresee the implementation of a particulate number (PN) requirement for all spark ignition (SI) vehicles with the introduction of EURO 6. Measurements with state of the art gasoline engine powered vehicles show that conventional MPFI engines are already below the future proposed limits while gasoline engines with direct injection are above these limits and will require additional development efforts.

This paper discusses both fuel system component requirements as well as control strategies in support of reducing particulate emissions. On the component side, mixture formation in regard to evaporation rate and penetration is a key factor. On the control side, injection timing and injection splitting are important parameters, especially under cold catalyst heating conditions. Encouraging test results show that significant improvements in regard to particulate matter emissions can be made. For the particulate mass emission a value significantly lower than the proposed limit can be achieved, while the proposed particulate number limit is significantly more challenging. The demonstrated vehicle results detailed below show that the proposed EURO 6 targets can be met by gasoline engines with direct injection by careful further optimization of the involved hardware and calibration without adding an additional after-treatment system.

INTRODUCTION

Improving the overall efficiency of gasoline powered passenger cars is the main focus of today's engine combustion development work. A remarkable number of different gasoline engine concepts are already in production or under development depending on market specific requirements. No common gasoline engine technology and architecture is identified yet. Gasoline engines operated under stoichiometric conditions can fulfill all current global exhaust gas emission requirements due to the very effective exhaust after treatment systems based on a three-way catalyst (TWC). For lean stratified engines the NO_x emissions will remain a challenge both from the point of view of conversion efficiency over lifetime and overall system cost. One of the major current gasoline engine trends is to downsize and boost in combination with direct gasoline injection. These measures lead to the usage of higher load points with improved combustion efficiency, while maintaining the drivability and NVH characteristics typical for gasoline engines.

The new emission standard EURO 5a introduced in September 2009 defines the particulate matter mass emission limits for Diesel and for the first time also for gasoline fueled engines with direct injection (GDi). The more stringent emission limits of EURO 5a compared to EURO 4 have led to the introduction of particulate filters in many Diesel applications while for gasoline engines a refined calibration is sufficient to be significantly below the limit. With the introduction of EURO 5b in September 2011, a limit for particulate number for Diesel powertrains will be introduced [1]. Although under discussion it is expected that the same limit will be introduced for gasoline powered vehicles with EURO 6 as shown in [Table 1](#).

Table 1. Past, current and proposed future European Emission Standards

		Gasoline				Diesel			
		EURO4	EURO 5a	EURO 5b	EURO 6	EURO4	EURO 5a	EURO 5b	EURO 6
		Jan. 2005	Sept. 2009	Sept. 2011	Sept. 2014	Jan. 2005	Sept. 2009	Sept. 2011	Sept. 2014
THC	mg/km	100	100	100	100	-	-	-	-
NMHC	mg/km	-	68	68	68	-	-	-	-
HC+NOx		-	-	-	-	300	230	230	170
NOx	mg/km	80	60	60	60	250	180	180	80
CO	mg/km	1000	1000	1000	1000	500	500	500	500
PM	mg/km	-	5*	4.5*	4.5*	25	5	4.5	4.5
PN#	#/km	-	-	-	TBD**	-	-	6.0E+11	6.0E+11

Status: September 2010

*for GDi engines only

**for all gasoline engines

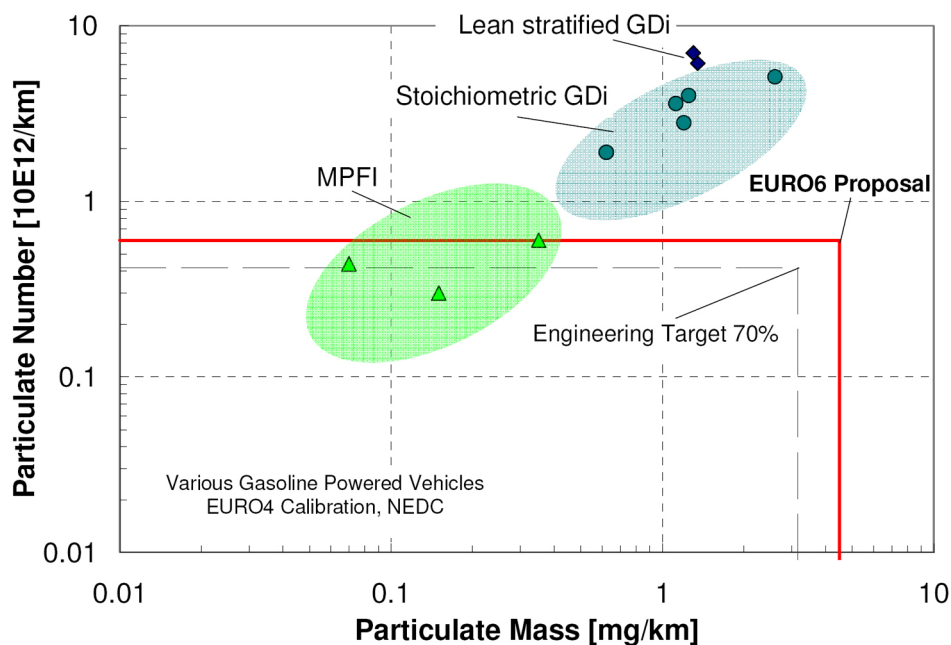


Figure 1. Vehicle emission proposal for EURO 6 (first step engineering target: 70%) - Status June 2010

Looking at particulate mass and number emissions measured on production vehicles with EURO 4 calibration in [Figure 1](#), it becomes obvious that the discussed particulate number targets will be a significant challenge for gasoline engines with direct injection - independently from homogenous or stratified operation modes - while the particulate mass limits can be easily achieved.

For port fueled injection engines (MPFI) the PM is already more than an order of magnitude lower, while the PN limit will require some refined calibration work to be sufficiently below the target value. [Figure 1](#) also reflects a weak correlation between PM and PN for gasoline powered vehicles for very low emissions.

Looking to the time-resolved particulate emissions of a EURO 4 calibrated vehicle with gasoline direct injection

during the European Driving Cycle (NEDC) in [Figure 2](#), several conclusions can be derived. A major amount of particulate mass and number is emitted in the early phase when the engine is cold and the catalyst system is still not fully operational. All the transient load and speed steps cause a steep increase of particulate emissions.

Since particulate emissions were not a priority in the calibration process previous to EURO 5, it can be assumed that a significant reduction will be achieved by optimization of engine control parameters with respect to particulate mass and number.

The injection system as a key element in the combustion system is responsible for the delivery of the demanded fuel mass at the correct timing and with the appropriate quality of atomization. All three parameters interact with other engine

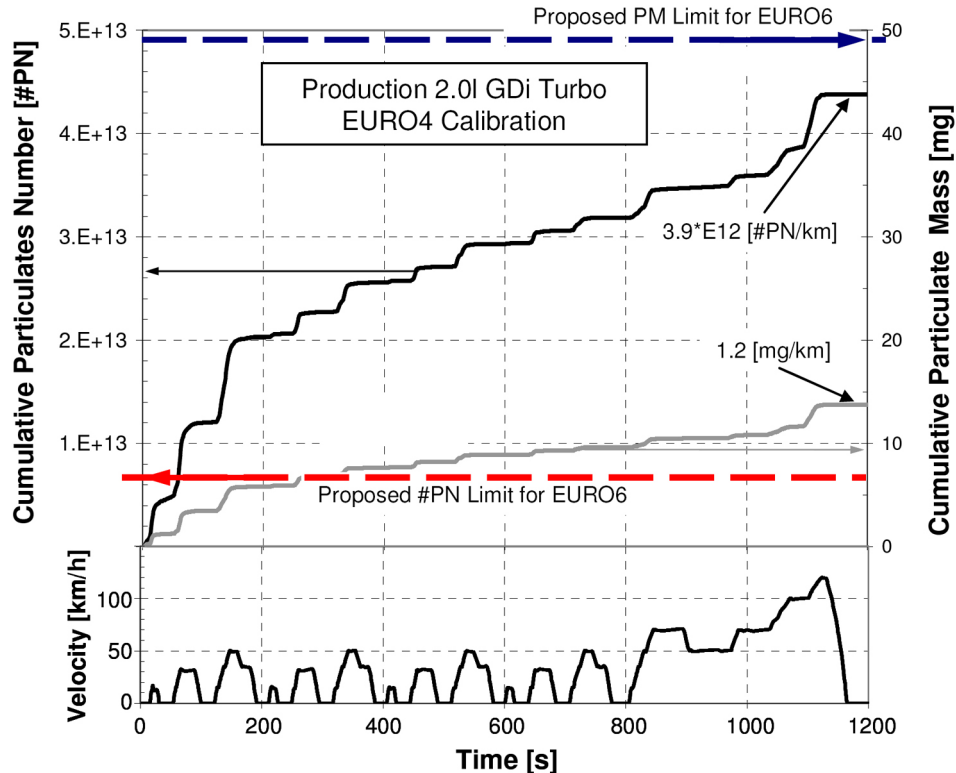


Figure 2. Time-resolved Particulate Emissions in the NEDC - EURO 4 Calibration

parameters such as air delivery, charge motion, etc. and determine the mixture preparation, which ultimately determines the combustion process and the emission characteristics. It is generally anticipated that the shorter time for mixture preparation - evaporation and homogenization - and in-cylinder spray-wall interactions are responsible for the higher particulate emission of GDi engine powered vehicles. The present article gives an overview of the development work performed at Delphi Powertrain Systems with the focus of reducing particulate engine out emissions of GDi engines.

PARTICULATE MATTER FORMATION IN GASOLINE ENGINES

The exhaust gas of internal combustion engines is a complex mixture of gaseous compounds, liquid and solid species. All components of the exhaust gas that can be trapped by a filter are considered to be particulate matter. These particles consist of elemental carbon (EC) also known as soot, an organic fraction with high and low volatility, ash from lubricants and metallic particles from wear [2]. While the particulate formation process for Diesel combustion is well investigated and documented [2], only very limited published material is available dealing with particulate formation during the combustion process of spark ignited engines [3][4].

EC can be formed during the combustion process in areas of locally rich combustion conditions. In the absence of oxygen and at temperatures above 400°C the hydrocarbon (HC) compounds from fuel or lubrication oil are decomposed into radicals and smaller molecules (pyrolysis), in particular acetylene. Those first radicals start to create polycyclic molecules (PAH's), which are the precursors to soot particles. The combination of these pre-cursors with HC molecules and other species form small soot particles (inception). Further dehydrogenation and combination of the species lead to a fast growth to larger particles (surface growth). In the coagulation phase larger particles are formed by accumulation governed by physical processes. These larger particles form agglomerates of a non spherical shape [5]. This step is characterized by a reduction of the particle number. Later in the combustion process most of the generated soot is oxidized and so typically only a smaller amount of soot is entering the exhaust system [3]. The conditions in the combustion chamber will determine the degree of oxidation: high temperatures and sufficient oxidation promoters like oxygen or OH radicals are the main factors of influence.

Pre-mixed combustion is dominant in gasoline engines, nevertheless inhomogeneities in the mixture can lead to locally rich areas which cause the formation of particulate matter [6]. Especially with GDi engines rich regimes can be found due to insufficient evaporation and mixing with air forming EC and volatile organic fractions. Mixture

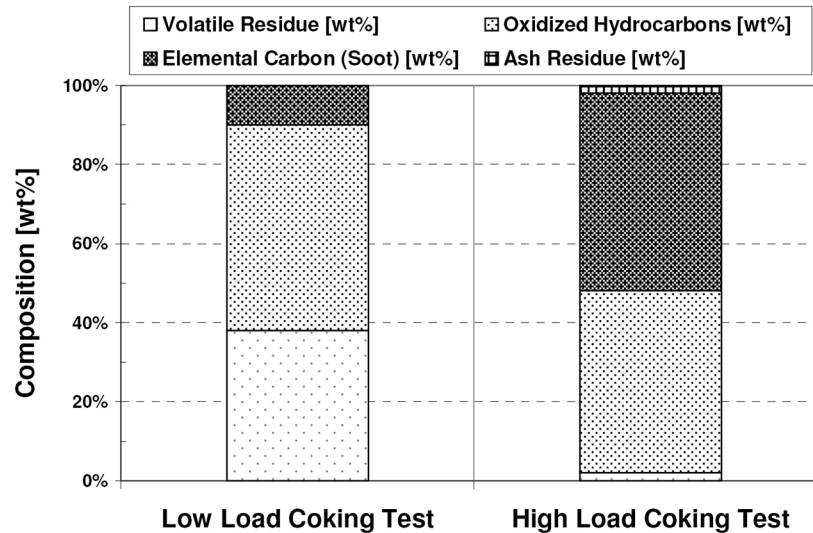


Figure 3. Coking Deposit Composition at different Operating Conditions of a GDI engine

deficiencies are also found close to combustion chamber walls when fuel is deposited and excessive soot formation occurs due to so called pool fires. In addition particulate matter consisting of volatile organic fraction is generated due to incomplete oxidation processes as the flame extinguishes. In the vicinity of the combustion chamber walls the in-cylinder oxidation of the generated particulates is limited and combustion ends consequently with a high amount of engine out particulates. Especially at cold start and warm-up engine conditions this trend is amplified as the evaporation of the fuel wall film is reduced and the turbulent mixing with the air is limited due to low engine speeds.

Overall, gasoline engine exhaust particles consist of similar materials and have a comparable morphology to Diesel particles. However, the number size distribution shows for homogeneous gasoline engines compared to Diesel engines typically a higher number of particles at smaller sizes [6]. Contrary to “typical” Diesel particulate matter, the majority of the particulates in gasoline engines is not composed of elementary carbon, but consists of high and low volatile compounds which are highly dependent on the operating conditions [7]. In [Figure 3](#) the composition of deposits for two different coking tests in a GDI engine are shown. This data confirms the strong dependence of the deposit composition on the engine operation conditions.

The success of the mixture formation process determines the final engine out particulate emissions. Therefore the optimization of the injection process and the subsequent mixing while minimizing wall films are global guidelines for low particulate emissions. With respect to fuel wall films, GDI engine architectures with a central mount injector configuration should therefore have an advantage over side mounted configurations where the piston wall is used to

guide injected fuel towards the center of the combustion chamber specifically in the catalyst heating mode.

PARTICULATE EMISSION OF GASOLINE ENGINES

Reduced particulate matter emissions result from minimizing the particle formation itself, as well as from optimizing particle oxidation in the combustion chamber and in the exhaust system. Clearly the injection process greatly influences mixture formation through mixture homogeneity and the potential presence of non-vaporized droplets and wall films. Other factors however, do also contribute to particulate emissions [8]. [Figure 4](#) outlines the most important high level functions in order to minimize the particulate matter tailpipe emissions of a GDI engine.

Generally high exhaust gas temperatures and the presence of residual oxygen are required for an efficient oxidation at the end of the combustion process both in the combustion chamber and also in the exhaust system. This implies that engine control parameters promoting those two key engine characteristics for low particulate emissions need to be fully utilized. At a given engine load and speed retarding the spark timing leads to a delayed combustion with an increased exhaust gas temperature thus lowering particulates. However retarded ignition leads to a fuel consumption penalty and is therefore only used during catalyst light off.

An engine configuration with a fast warm-up of the combustion chamber walls helps to minimize the stored liquid fuel in wall films on the piston surface and the cylinder liner and in deposit layers. Engine oil in the combustion chamber introduced either via the lubrication path at the cylinder walls or via the intake ports contributes to particle formation. The higher evaporation temperature of the oil

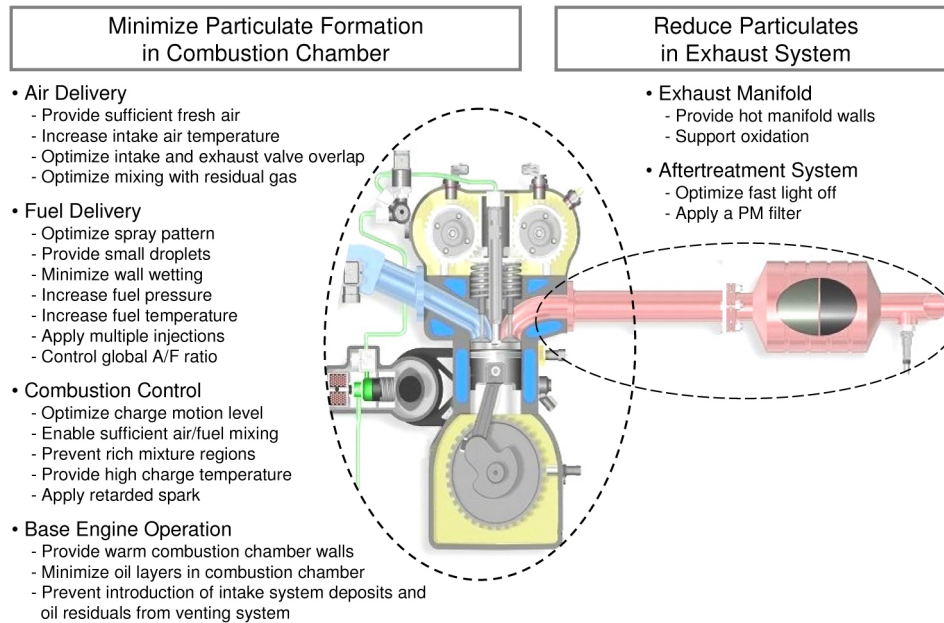


Figure 4. Functions to minimize Particulate Emission from Gasoline Engines

constituents results in incomplete vaporization and a less effective mixture with air.

The cold start and warm-up phase contributes strongly to the overall particulate matter emissions as the engine is not yet at operating temperature and therefore particles consisting of volatile residues cannot be effectively oxidized. In consequence, similar to conventional gaseous emissions, any measure to shorten the warm-up phase will help to reduce both the particulate mass and the particulate number [9].

In principle, particulate filters already in standard use on modern Diesel engine powered passenger cars can be applied to gasoline engines as well [10]. The typically smaller particles generated by gasoline engines require a finer filter characteristics (e.g. cell density, mean pore size and porosity) which consequently leads to a higher exhaust system backpressure with a negative impact on performance, fuel consumption and CO₂ emissions. The addition of a particulate filter system would cause a significant increase of the overall after-treatment system complexity and cost.

PARTICULATE REDUCTION BY OPTIMIZED OPERATION

VALVE TRAIN

Mixture quality is critically influenced by the successful atomization and subsequent evaporation of fuel and an adequate mixing with air. In addition to the injection process the optimization of the air path is important in order to provide fresh air and adequate charge motion levels for mixing and flame front propagation. To understand the

influence of cam timing on particulate number emissions a series of tests were performed on a single cylinder engine. During warm engine operating conditions particulate mass and particulate number emissions were at a very low level. Influences of either intake or exhaust cam timing variation were negligible. However, at cold operation (50°C coolant temperature) a more significant effect of cam timing could be observed. At low part load conditions (2000 rpm and 3 bar NMEP) an increase in hot internal EGR, established by trapping exhaust gas in the combustion chamber with early EVC, was identified to reduce particulate number emissions by almost 40%. Increasing hot internal EGR by means of recuperating exhaust gas from the outlet port with late EVC did also show a reduction of particulate number emissions, but to a lesser degree of 20%. Both effects diminish when going to higher load and speed conditions. A higher percentage of hot EGR in the lower load condition provides higher mixture temperatures with better vaporization and helps to reduce particulate number emissions under these cold conditions. Varying intake valve timing, with the exhaust cam in the mid position, showed significant decrease in particulate number emissions of up to 55% with late IVC. As can be seen in [Figure 5](#) in this low load/speed conditions the variation of the valve timing had little effect on HC emissions in contrast to the strong influence on particulate matter emissions.

ENGINE TEMPERATURE

Single cylinder engine testing has been performed at various fixed engine oil and coolant temperatures and at different injection timings for single pulse operation. [Figure 6](#) shows the particulate emissions at two steady state engine