

Application of Catalyzed Gasoline Particulate Filters to GDI Vehicles

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ABSTRACT

With the introduction of limits for particle numbers besides particle mass emitted by light duty vehicles new pollution control devices like catalyzed gasoline particulate filters (GPF) might be required. GPFs need to address the challenge to provide sufficient particle number reduction at acceptable pressure drop in addition while having high conversion efficiencies for regulated pollutants.

The emission performance of gasoline particulate filters coated with a three-way functional washcoat was examined. The impact of the washcoat on particle filtration efficiency was investigated, as well as its impact on the conversion efficiencies for hydrocarbons, carbon monoxide and nitrous oxides. Moreover, it was found that the precious metal containing washcoat accelerates the regeneration of a filter when loaded with artificial soot.

In addition, an emission study was performed on exhaust systems comprising a three-way catalyst (TWC) on a flow through substrate and a gasoline particulate filter. The influence of precious metal distribution between TWC and GPF on hydrocarbon, carbon monoxide and nitrous oxides emissions will be discussed. With optimized distribution of precious metals between TWC and GPF tailpipe NO_x emissions can be decreased substantially.

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INTRODUCTION

Gasoline direct injected (GDI) vehicles with and without turbocharger are gaining market share in Europe due to their superior fuel economy and drivability when compared to port fuel injection vehicles [1,2]. This trend is expected to continue due to the mandate of the European Union to passenger car manufacturers to further decrease CO₂ emissions and meet a fleet average of 130 g/km CO₂ emissions in 2012. More ambitious CO₂ fleet average targets are under discussion [3]. With CAFE standards becoming more demanding in the United States it is generally anticipated that in North America the share of GDI vehicles will grow at the expense of PFI vehicles.

A concern related to GDI vehicles is the particle emission originating from this engine type, especially due to the relatively small particle sizes and therefore potentially more hazardous nature of these particles [4]. Since the implementation of Euro 5b emission legislation stage in the beginning of 2011 all new registered diesel passenger cars have to comply with a particulate mass limit of 4.5 mg/km as well as with a solid particle number limit of 6×10^{11} #/km, (see Table 1). The introduction of a particle number limit for

gasoline vehicles was postponed to the Euro 6 emission legislation stage which will come into effect September 2014 [5]. It is anticipated that the limits for spark ignited vehicles will be the same as those for compression ignited vehicles to arrive at technology neutral emission legislation.

Table 1. Euro 6 emission limits for passenger cars

		compression ignition vehicles	spark ignition vehicles
THC	mg / km	n.a.	100
NMHC	mg / km	n.a.	68
HC+NO _x	mg / km	170	n.a.
NO _x	mg / km	80	60
CO	mg / km	500	1000
particle mass	mg / km	4.5	4.5
particle number	# / km	6.0×10^{11}	TBD

Gasoline vehicles with port-fuel injection usually comply with the proposed particle emission target of 600 billion particles per kilometer. There is no published data in the literature of gasoline direct injection vehicles complying with the proposed limit without the use of a particulate filter [6]. This finding was confirmed by a study of the Joint Research Center of the European Commission [7]. A study by Braisher et al. revealed that particle number emissions by spray-guided direct injection vehicles were over a magnitude higher than with port-fuel injection vehicles with a large portion of the particles being emitted during the cold start of the driving cycle [8]. Particulate mass emissions exhibited the same trend.

Several studies have shown that only wall-flow filters are effective in reducing the particle number emissions below the target of 6×10^{11} #/km. For instance, Ericsson compared a ceramic substrate with straight channels to metallic and ceramic flow-through filters having channel obstacles to a wall-flow filter. The wall flow filter was the most efficient at reducing particulate number emissions. [9] In another study it was found that on a 2.0 L homogeneous direct injection vehicle the proposed Euro 6 particle number targets could be safely met in all cases when applying a ceramic wall-flow filter while the raw emissions were significantly above the limit. In this study the volumetric ratio of engine displacement to GPF was varied between 1.4 and 3.5. For all investigated volumetric ratios ($V_{\text{engine displacement}} / V_{\text{filter}}$) the legislative targets could easily be met [10].

Cordierite-type wall-flow filters have become a standard solution for heavy duty diesel vehicles and have also gained a lot of consideration for passenger car diesel applications [11]. Recent studies have shown the successful application of cordierite filters for the particle exhaust treatment of GDI vehicles [12].

In this paper we shall present an examination of the applicability of gasoline particulate filters with a washcoat function for three-way catalysis on two GDI vehicles. A GPF was added to these vehicles in an underbody position. An examination of the GPFs impact on the regulated exhaust emissions as well as on backpressure and fuel economy will be provided. It will be demonstrated that by optimizing PGM distribution between close-coupled TWC and underbody GPF, improved efficiency for abatement of regulated pollutants can be achieved. In a second set of experiments the underfloor three-way catalyst was removed from the serial exhaust aftertreatment system and replaced by catalyzed GPF samples. It will be demonstrated that this replacement can be implemented emission neutral at no additional precious metal costs. The influence of substrate cell density and washcoat uptake on emissions will also be discussed.

EVALUATION OF ADD-ON GASOLINE PARTICULATE FILTERS

EXPERIMENTAL SETUP

Two different modern stoichiometric DI (direct injection) applications were used for the GPF investigations, a 2.0 L turbocharged GDI (GTDI) vehicle and a 1.4 L turbocharged GDI engine on a high dynamic engine bench. Both engines have an air- /wall-guided injection system with side mounted fuel injectors. In Figure 1 a schematic experimental set up is shown. Emission analyzers (AVL/Pierburg AMA4000) were used to measure the gaseous emission CO, CO₂, NO_x, THC and O₂. Exhaust gas sensors are located 2" before and after the TWC and after the GPF. Thermocouples and pressure sensor were located in similar positions for temperature and back pressure measurement. Additional lambda sensors were used to measure air-fuel ratio. A Horiba MEXA1000 was used to measure particulate number according to PMP. As particulate number PN was measured undiluted after the GPF, the additional dilution step from MEXA1000 was used. The instrument was able to provide time-resolved particle number data.

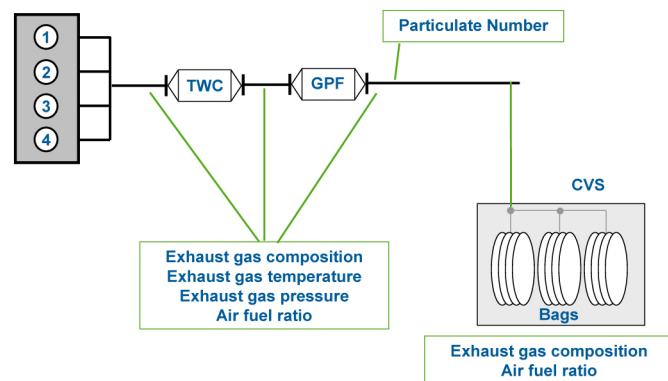


Figure 1. Experimental setup and diagram of instrumentation locations.

Four systems were built and evaluated on two DI engines, (see Figure 2). The "Reference" consisted only of the production TWC catalyst. The Reference system uses a 101.6 mm diameter substrate by 152 mm in length. The cell density is 600 cpsi. System1 and 2 used the same Reference TWC catalyst technology with an uncatalyzed and catalyzed GPF system, respectively in the underfloor location. System 3 used a PGM zoned TWC catalyst with a catalyzed GPF. All the GPF substrates are made of cordierite material with a 65% porosity and a large mean pore size of $\geq 20 \mu\text{m}$. Substrate dimensions are 118.4 mm in diameter by 152 mm in length. Cell density and wall thickness are 300 cpsi with 12 mil wall thickness. The filter substrates were coated with washcoat slurry having a three-way functional composition specifically optimized for usage in GPFs. The precious metal loadings of both close-coupled TWC and underbody GPF can be found in Table 2. All systems with catalyzed GPF that were evaluated

in this study have lower precious metal costs than the Reference system. All systems were aged in parallel after a fuel-cut aging procedure with a bed temperature of 1030 °C.

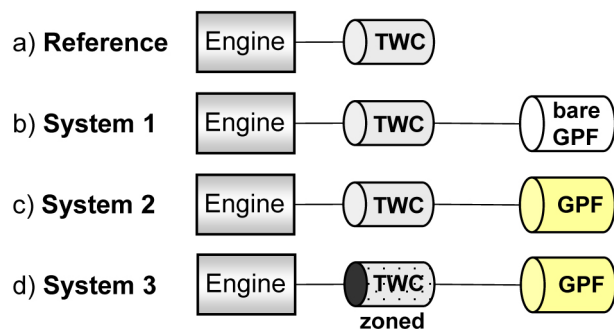


Figure 2. Samples evaluated in NEDC on 2.0 L GTDI vehicle and high dynamic engine bench: a) Reference system; b) test system with uncoated GPF in underbody position c) test system with coated GPF in underbody position d) test system with zoned close coupled TWC and coated GPF in underbody position.

Table 2. Precious metal loadings and costs of systems shown in Figure 2. Precious metal prices as of August 2011.

	Pd/Rh g/ft ³		PGM cost \$	
	TWC	GPF	TWC	GPF
Reference	56/4		69.16	
System 1	56/4	0	69.16	
System 2	52/3	2/1	62.37	6.38
System 3	46 ^a /4	2/1	58.66	6.38
^a Pd zoning: 3" inlet 76 g/ft ³ , 3" outlet 16 g/ft ³				

TEST RESULTS ON A 2.0 L GTDI VEHICLE

For the application study of catalyzed GPFs two different stoichiometric GDI vehicles were chosen: The first one was a 2010 MY vehicle with a 2.0 L direct injection engine with turbo charger. This vehicle is calibrated for Euro 5 and has a 1.4 L production catalyst located in close-coupled position. This vehicle was tested on a chassis dyno equipped with a CVS system for bag analysis, has three online analyzer lines (raw gas, after TWC and after GPF) for gaseous emission components and a particulate counter (Horiba MEXA 1000) that was used in undiluted measurement configuration after the GPF. To measure according to PMP it uses an additional dilution step. All results shown are the average values of at least three tests.

PARTICLE EMISSION TEST RESULTS

The particle number emissions measured in the New European Driving Cycle (NEDC) of the four exhaust systems described in Figure 2 are shown in Figure 3. The particulate number emissions profile of the TWC only reference system is identical to the raw emissions of the vehicle (4.0×10^{12} #/km). There is no measurable particle number abatement from the three-way catalyst on a flow-through substrate. The graph indicates that particle emissions are emitted during the entire cycle with the majority of the emissions occurring during the cold start period and the accelerations during the ECE portion of the test. Systems 1 to 3 equipped with gasoline particulate filters reduce the amount of emitted particles drastically. The graphs in Figure 3 show that all 3 systems, while already minimizing the particle emissions during cold start, are able to almost completely suppress particle emissions from the system during the warmed-up operation. Figure 4 summarizes the particle emissions and the filtration efficiency. The filtration efficiency of each aftertreatment system was calculated based on the measurements at the engine-out and 2" after the underfloor canning of the system. Each value represents the average from three NEDC tests. With the chosen cordierite type filter the filtration efficiency of System 1 is 84% resulting in emission of 6.4×10^{11} #/km. By applying a washcoat to the filter the filtration efficiency increased to 95% and 93% for System 2 and System 3 resulting in 2.0×10^{11} #/km and 2.4×10^{11} #/km respectively. Both systems safely meet the proposed limits. The increased filtration efficiency is expected as with application of washcoat the mean pore diameter of the substrate wall pores is slightly decreased.

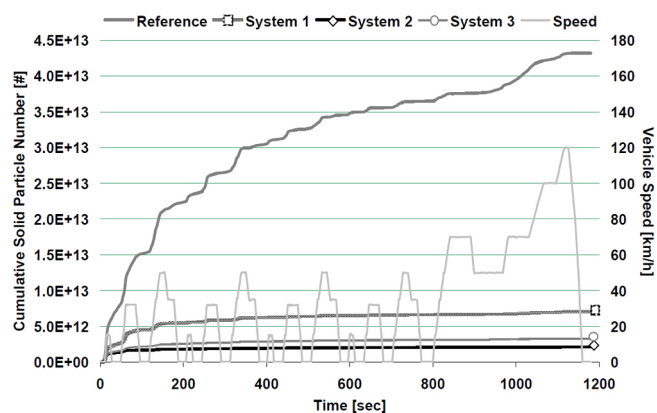


Figure 3. 2.0 L GTDI NEDC solid particle number emissions profile.