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Cost effectiveness of particulate filter installation on Direct Injection Gasoline vehicles

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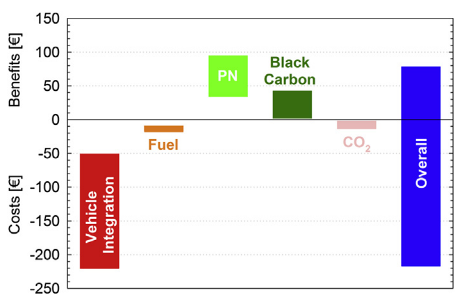
HIGHLIGHTS

- We project the particle number emissions from diesels and gasolines in EU up to 2030.
- We quantify the vehicle integration cost for Gasoline Particulate Filters (GPF).
- We estimate the environmental benefits and penalties resulting from GPF installation.

GRAPHICAL ABSTRACT



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ABSTRACT

The recent introduction of a Particle Number (PN) limit of 6×10^{11} # km^{-1} for all Direct Injection Gasoline (GDI) vehicles registered in Europe after September 2017, is expected to necessitate a widespread application of Gasoline Particulate Filters (GPF). It is therefore important to assess whether the associated implementation costs can be justified on the basis of the societal benefits. Monetary valuation of externalities originating from the reduction of Particle Number and Black Carbon emissions, accounting for any fuel consumption and Carbon Dioxide penalties, provided evidence that a GPF installation can be a cost effective solution. Emission projections up to 2030, revealed that the three year delay in the implementation year, will introduce a relatively limited burden on future air quality, owing to the currently limited population of GDIs.

1. Introduction

Exposure to ambient Particulate Matter (PM) has been associated with adverse health effects in a number of epidemiological (e.g. Pope, 2000) and toxicological (e.g. Oberdörster, 2000) studies. Automotive exhaust has long been identified as one of the major contributors to anthropogenic PM, stimulating regulatory authorities worldwide to introduce continuously tighter PM emission limits in the vehicle certification procedure.

In Europe, the regulation initially tackled only diesel engines, owing to their considerably higher emissions compared to their gasoline counterparts. The situation however started changing nearly a decade ago with the first successful application of wall flow Diesel Particulate Filters (DPF) (Salvat et al., 2000). The proven robustness of the DPF systems (Jeuland et al., 2004) and the increasing evidence on the toxicity of diesel PM that was already classified as carcinogenic (California EPA, 1998) with no safe exposure levels (COM, 2005), led in decision to mandate the

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installation of best available DPF systems in all diesel vehicles registered after 2011 (EC, 2008). Recognizing that the gravimetric procedure is not sensitive enough to discriminate between wall flow and the much less efficient flow-through DPF systems, the 80% reduction in the PM limit (4.5 mg km^{-1}) was accompanied by the introduction of a non-volatile Particle Number (PN[1]) limit of 6×10^{11} # km^{-1} on the basis of the findings of the Particle Measurement Program (PMP) (Giechaskiel et al., 2012).

While the health effects of gasoline exhaust particles were not investigated as much, a number of studies suggested similar toxicity per mass of PM emitted (e.g. Geller et al., 2006). Meanwhile, the legislated steps taken towardtoward the reduction of the greenhouse emissions (EC, 2009; USEPA, 2010) led in a gradual replacement of conventional Port Fuel Injection (PFI) engines with their more efficient Direct Injection Gasoline (GDI) counterparts. It is estimated that by 2017 40–60% of all new registered gasoline vehicles in Europe will incorporate GDI engines (Mamakos et al., 2012a). The fuel efficiency benefit of GDI engines however, comes at the expense of elevated particulate emissions, which could even exceed 10 mg km^{-1} for some of the first generation vehicles (Ntziachristos et al., 2004). Accordingly, the Euro 5a (applicable from September 2009) PM limit of 4.5 mg km^{-1} was extended for the first time in this family of gasoline vehicles (EC, 2007). The same regulation also envisaged the introduction of a PN limit for gasoline vehicles, with a threshold to be defined not later than September 2014.

The deteriorated particle emission performance of GDI vehicles becomes more evident when employing the more sensitive PN measurement procedure, in which case the diesel PN limit of 6×10^{11} # km^{-1} can be exceeded by up to one and a half orders of magnitude (Mamakos et al., 2012b). The foreseen regulation of gasoline PN emissions stimulated significant research efforts on measures to improve the emission performance of GDI vehicles. A number of studies already indicated that large PN reductions can be achieved through optimization of the injection strategy (Piock et al., 2010) or even the use of advanced engine designs (Heiduk et al., 2011). It is not clear though whether such internal engine measures will suffice, especially considering the anticipated regulatory requirements for emission compliance under real world operation (EC, 2007). At this stage the only proven technology that would effectively bring the PN emissions of GDI vehicles below 6×10^{11} # km^{-1} is wall flow Particulate Filters optimized for gasoline vehicles (GPF) (Mikulic et al., 2010; Saito et al., 2011). Therefore, a decision on the suitability of the diesel PN limit on GDI vehicles should be based on the cost effectiveness of such GPF solutions.

In the present study we quantify the relative merits of a GPF installation on GDI vehicles, on the basis of published material and confidential information provided by GPF and automotive manufacturers. The analysis takes into consideration the effect on particle number, Black Carbon and carbon dioxide emissions as well as the associated implementation cost and fuel penalty. The results of this study formed the basis for the decision taken by the EU member states to introduce a PN limit of 6×10^{11} # km^{-1} at a Euro 6 stage (September 2014), allowing for a relaxed threshold of 6×10^{12} # km^{-1} over the first three years (EC, 2012).

2. Methodology

The cost effectiveness of a GPF solution was based on the associated costs and societal benefits over the useful life of the European fleet average GDI vehicle, taking into consideration the spatial distribution of vehicle activities and externalities across the EU 27 member states, as described in the following sections. In lack of information on the effect of a potential delay in the GDI PN regulation on the implementation cost, this issue was only investigated with respect to its effect on the projected total PN emissions from Passenger Cars (PCs) and Light Duty Vehicles[2] (LDVs) in Europe in the timeframe 2000–2030. More details on the methodology can be found in Mamakos et al. (2012a).

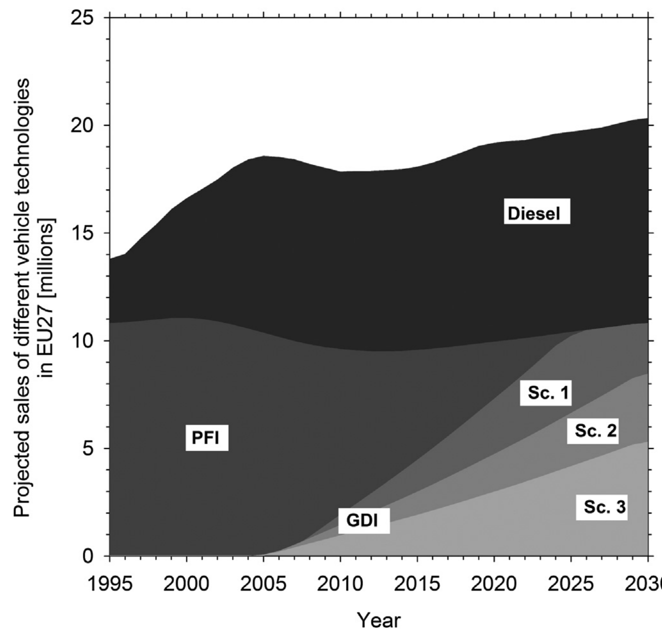

Fig. 1. Projected sales of vehicles in EU 27 for the three scenarios examined, categorized according to the engine concept.

2.1. Emission projections

2.1.1. Fleet evolution

The TREMOVE model (TREMOVE, 2010 - version 3.1.1) was employed to project the population of vehicles in the 27 European Member states up to 2030. Since the TREMOVE model does not discriminate between PFIs and GDIs, an assumption was made for the relative share of the later in the new registered gasoline vehicles. Three scenarios were investigated on the basis of information provided by GPF and automotive manufacturers. Fig. 1 illustrates the projected sales of GDI, PFI and diesel vehicles in Europe, assumed in the study.

The TREMOVE data allowed for further classification of the vehicles into three size classes corresponding to Small Passenger Cars (SPC, equipped with engines smaller than 1.4 dm^3), Medium and Large Passenger Cars (MLPC, with engine displacement larger than 1.4 dm^3) and Light Duty Vehicles (LDV). This categorization was necessary as the size, and therefore cost, of the GPF should scale with the engine displacement. The vehicles were further subdivided into emission technology classes, corresponding to the implementation dates of the different emission standards introduced in Europe. This approach incorporates the inherent assumption that the improved emission performance of vehicles already complying with future legislation is counterbalanced by the sales of older technology vehicles in the transition period.

1 In the context of this paper, PN stands for tailpipe non-volatile particle number emissions as defined in the European legislation. This also implies a nominal 50% cut-off size at 23 nm.

2 Commercial carrier vehicles with a gross vehicle weight of not more than 3. 5 tonnes.