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A Technical Overview of Particulate Exhaust Emissions in the Post-RDE Era

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Abstract

The subject of exhaust particulate emissions from road vehicles continues to gain attention and further, more stringent legislative demands are expected in this area. While the European Union has been at the forefront in recent decades, other jurisdictions are making progress towards more comprehensive control and limitation of exhaust particulate. This technical overview examines past, current and likely future (Euro 7) legislative requirements and also presents sample results from a range of vehicle types, in order to make comparisons and discuss the impact of expected regulatory updates. The impacts of powertrain trends, including hybridization, on exhaust particulate emissions and their control are briefly analyzed. Regulatory trends including the intention to move the lower boundary of the size range considered from 23 nm to 10 nm and the elimination of fuel- and technology-specific limits on particulate emissions are discussed and their implications analyzed. The impact of test conditions and the demands placed on aftertreatment systems are identified based on examples from the literature and the authors' own results presented in this work. Finally, some comments on considerations for the topic of exhaust particulate measurement and control for the coming years are offered.

Introduction

Ongoing concern over exhaust emission from the road transport sector continue to motivate changes to legal requirements to force new vehicles to emit at much lower levels than in the past. Indeed, reduction of the level of harmful exhaust emissions today, especially NO_x for diesel light duty engines and particle number (PN) for gasoline direct injection (DI) engines, are among the main drivers influencing development of personal transport [1, 2, 3]. The regulation of particulate emissions from vehicles' tailpipes has a long history; in the EU, the "traditional" gravimetric measurement of particulate emissions was introduced thirty years ago and the particle number (PN) method almost a decade ago for diesel light-duty vehicles, followed later by veicles with direct injection spark ignition engines.

While the term "exhaust gas" naturally brings to mind gaseous species, the complex mixture of combustion products emitted by combustion engines also contains non-gaseous pollutants. The nature, type and - crucially - concentration of such non-gaseous pollutants varies massively by engine and fuel type as well as by engine operating conditions and even measurement parameters. In contrast to most gaseous exhaust gas components, particulate has no fixed physical (or indeed chemical) structure and any given exhaust gas stream will contain a very wide variety of particle types, in terms of physicochemical characteristics. While much research focuses on the nature and properties of particulate formed in combustion reactions occurring in various engine types and involving various fuels, the legislative approach adopted in the EU is to set limits for the quantity of particulate emitted, defined in terms of the response of the narrowly-defined measurement procedure used for quantification.

This paper discusses current PN regulation, necessary control technologies, and impact of boundary conditions on PN emissions. The challenges for the future Euro 7 regulation are also discussed.

EU Legislative Requirements Concerning Particulate Emissions

For the last 10 years, the European Union (EU) has had two types of emissions limit in place for control of particulate emissions: gravimetric (particulate matter, PM mass) and number-based (particle number, PN), with prescribed measurement methods to match. For gravimetric (mass-based) limits, the approach is to pass a portion of the exhaust gas through a filter, with the change in filter mass being used to calculate the gravimetric emissions during the sampling

on-road trip to laboratory WLTP CO_2 value. For dynamic driving, but still within the boundary conditions this CO_2 ratio is around 1.5 [18,19]. Thus, currently a trip at -7°C, driven dynamically with emissions 2.1×10^{12} 1/km would be compliant. With Euro 7 these boundary conditions are expected to be "normal" without any correction factor (i.e. the PEMS uncertainty is included in the limit, and no corrections are applied at -7°C or dynamic driving), which translates to a 3.6 times stringency. Furthermore, sub-23 nm particles will be included. As discussed before, this is expected to increase the concentrations around 35%, but is powertrain-, fuel- and cycle-dependent. Furthermore, the minimum trip distance is expected to be somewhere between 5 and 16 km, thus the cold start emissions cannot be "diluted" with long trips. In addition, if regeneration takes place during the test, then the emissions over the regeneration distance have to be taken into account. Although not all "worst case" conditions will be encountered simultaneously, this theoretical example shows that the new provisions (sub-23 nm, minimum distance, regeneration) add another 2.5 times stringency. Putting it all together, an up to 8.8 times stringency with Euro 7 is expected, even keeping the same numeric PN limit. A reduction of 6 times of the limit, as proposed by CLOVE [31], would translate to a >50 times stringency.

Despite DPFs having been commercialized well over a decade ago, research and optimization work continues. For GPFs/OPFs, which operate in a very different thermochemical environment and which are a much less mature technology, research is arguably more intensive still, including the crucial topic of accurate diagnosis of state of the filter, its loading and the resulting flow resistance (back pressure) [32].

Summary/Conclusions

The EU is entering its fourth decade of automotive emissions control concerning particulate. While considerable progress has been made, even the latest emissions requirements (Euro 6d) remain somewhat fuel- and technology-specific, with large numbers of vehicles not subject to any legislative requirements regarding particulate emissions. This is a situation which should - and most likely will - change over the next few years. Exhaust emissions reduction is a key issue for further vehicle and powertrain development; simultaneous reduction of fuel consumption/CO_2 emissions, as well as regulated gaseous and particulate emissions still remains a challenge. The scale of the challenge is widely expected to increase in the near future - i.e. with further regulations emissions (e.g. Euro 7). EU requirements may serve as inspiration for other markets considering adopting PN limits (the USA, Japan), as well as for lower-income countries starting to increase the stringency of their lax exhaust emissions requirements (or even introducing them for the first time).

The very wide range boundary conditions considered valid during RDE testing, as well as planned moves to loosen the set of requirements that define "normal vehicle usage", create a very wide set of circumstances under which compliance of emissions requirements must be demonstrated at type approval and guaranteed for a portion of the vehicle's useful life. Euro 7 is also very likely to increase the mileage/age considered the upper limit of full useful life, thereby increasing the scale of the durability challenge. Fuel-neutral emissions limits are expected, meaning that all light duty vehicles with a combustion engine will be subject to the same emissions limit, including for particulate.

A simplified analysis showed that only the new provisions (i.e. no conformity factor, wider boundary conditions, inclusion of sub-23 nm particles, smaller minimum distance) increase the stringency more than 8 times, in addition to any reduction of the current limit.

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Definitions/Abbreviations

λ - lambda; the relative air:fuel ratio

CI - compression ignition