European
Commission

JRC SCIENCE AND POLICY REPORTS

Durability Demonstration Procedures of Emission Control Devices for Euro 6 Vehicles

Final Report

Maria Cristina Galassi
Giorgio Martini

2014

Report EUR 26435 EN

Joint
Research
Centre

European Commission
Joint Research Centre
Institute for Institute for Energy and Transport

Contact information
Maria Cristina Galassi
Address: Joint Research Centre, Via Enrico Fermi 2749, TP 441, 21027 Ispra (VA), Italy
E-mail: maria-cristina.galassi@ec.europa.eu
Tel.: +39 0332 78 9371

https://ec.europa.eu/jrc

JRC87070

EUR 26435 EN

ISBN 978-92-79-35087-0 (PDF)
ISBN 978-92-79-35088-7 (print)

ISSN 1831-9424 (online)
ISSN 1018-5593 (print)

doi:10.2789/18532

Luxembourg: Publications Office of the European Union, 2014

Abstract

The implementation of increasingly demanding vehicle emissions standards fostered the improvement of existing aftertreatment technologies and the development of innovative solutions. In order to assure compliance with emissions limits not only for new registrations but also throughout vehicles' useful life, current legislation introduced emissions durability requirements, proposing tailored accelerated aging procedures or the application of assigned deterioration factors besides actual in-use driving. The present report aims at contributing to a deeper understanding of aftertreatment system aging mechanisms and methods in order to assess Euro-6 vehicles durability approach.

Contents

EXECUTIVE SUMMARY

The implementation in Europe of increasingly demanding vehicle emission standards over the last twenty years fostered the introduction of innovative after-treatment technologies in order to achieve the emission reduction targets. However, new emission standards and the related technologies are beneficial only if they actually lead to a significant reduction of emission levels under normal condition of use of the vehicles; this implies the compliance with emissions limits not only at type approval but also in real world driving conditions and throughout the useful life of vehicles. For this latter reason, durability requirements are included in the current European vehicle emission legislation. Demonstrating that a vehicle meets these durability requirements is not an easy task. The durability of after-treatment systems should ideally be verified by testing vehicles before and after these have accumulated the mileage prescribed by the legislation (160.000 km from Euro 5). Such tests are, however, expensive and time consuming. For the purpose of durability demonstration, the current legislation proposes also either accelerated ageing procedures tailored for positive-ignition (PI) and compression-ignition (CI) vehicles (i.e., conducted over the Standard Bench Cycle and Standard Diesel Bench Cycle, respectively) or the use of assigned deterioration factors. The European accelerated ageing procedure for vehicles with PI engine is based on well-established principles and directly derived from the relevant regulation in the USA [60]. On the other hand, the accelerated ageing procedure for CI vehicles was included in the Euro 5 legislation [3] in a late phase of its development process and upon a proposal of the automotive industry. At the time this procedure was very little discussed among the stakeholders and was not supported by robust validation data. As a consequence there are concerns that this procedure will not properly cover the real world deterioration mechanisms of after-treatment technologies needed to comply with the Euro 6 emission standards.

This report aims at contributing to a deeper understanding of (i) the aging mechanisms that are relevant for after-treatment systems of PI and CI vehicles and (ii) the available methods to assess the durability of Euro 6 vehicles.

An overview of the legislative background is provided at first, followed by a summary of the deterioration mechanisms that could affect the conversion efficiency of the most common after-treatment technologies.

Thermal ageing results to be the major pathway for the deactivation of all catalytic after-treatment devices (Three Way Catalyst, Diesel Oxidation Catalyst, Selective Catalytic Reduction, Lean NOx Trap), followed by ash plugging in the case of DOC, SCR and LNT. Ash deposition represents instead the most important degradation mechanism for particle filters (Diesel Particulate Filter, Gasoline Particulate Filter), together with soot plugging (from incomplete regeneration) for DPF. A summary of main findings on deterioration mechanisms is presented in the following Table.

Table ES 1: Most critical deterioration mechanisms

AFT Device	Thermal Deactivation	Chemical Poisoning	Mechanical/Physical	
			Plugging	Cracking
TWC	++	-	-	-
DOC	++	-	+ Ash	-
SCR	++	-	+ Ash	-
LNT	++	+ Sulphur	+ Ash	-
DPF	-	-	++ Ash & Soot	+
GPF	?	-	++ Ash	?

LEGEND: ++ primary, + average, - minor, ? no info available in the literature.

Current European provisions for durability demonstration are then presented, with focus on accelerated ageing procedures. The different degree of details and validation of the accelerated ageing procedure for vehicles with positive ignition engines compared to the procedure for compressed ignition engines has been identified as one of the main issues. In particular, the accelerated ageing procedure for PI vehicles appears to be appropriate for reproducing the main deterioration mechanism for three way catalysts, the thermal ageing. On the other hand, the accelerated ageing procedure for CI vehicles properly addresses the impact of the thermal ageing due to regenerations but does not cover adequately other deterioration sources significant for the ageing of diesel after-treatment systems (i.e. ash deposition and poisoning, thermal load between regeneration events). Further concern derives from the vague and not clear description in the Euro 5 standard of how the ageing procedure for compression engines should be practically implemented. Alternative approaches are presented and discussed. The DAAAC protocol developed by the Southwest Research Institute is proposed as an example of an at least partially validated procedure that could be used as inspiration for possible modifications to the current procedure for diesel vehicles.

Finally, a review of deterioration factors currently available for Euro 6-like vehicles certified in the USA is presented. The results (see **Table ES 2**) suggest that in the case of gasoline vehicles the Euro 5 assigned DFs for gaseous emissions are conservative compared to the vast majority of the declared DFs. The situation is quite different for PM, for which the real DFs seem to be higher than the Euro 5 assigned factor. As far as diesel vehicles are concerned, the 90th percentile of the declared DFs for NOx appears to be slightly higher than the Euro 5 assigned DF.

Table ES 2: Multiplicative DFs for Euro 6 vehicles

	CO	THC	NMHC	NOx	PM	CH_4
ASSIGNED Euro 5 - PI	*1.5*	*1.3*	*1.3*	*1.6*	*1.0*	
Derived Euro 6 – PI 90th percentile	1.224	1.189	1.153	1.500	1.321	1.764
ASSIGNED Euro 5 - CI	*1.5*			*1.1*	*1.0*	
Derived Euro 6 – CI 90th percentile	1.359	1.178	1.220	1.248	1.071	1.319

ABBREVIATIONS AND ACRONYMS

ADF	Assigned Deterioration Factor
AMA	Approved Mileage Accumulation Cycle
BAD	Bench Ageing Duration
BAT	Bench Ageing Time
DAAC	Diesel After-treatment Accelerated Ageing Cycle
DF	Deterioration Factor
DOC	Diesel Oxidation Catalyst
DPF	Diesel Particulate Filter
EC	European Commission
EDV	Emission Data Vehicle
EEC	European Economic Community
EEV	Enhanced Environmentally friendly Vehicle
EPA	Environmental Protection Agency (USA)
EU	European Union
FBC	Fuel Borne Catalyst
G-DI	Gasoline Direct Injection
GPF	Gasoline Particulate Filter
HC	Hydrocarbons
HDV	Heavy-Duty Vehicle
LDT	Light-Duty Truck
LDV	Light-Duty Vehicle
LNT	Lean NOx Trap
LPG	Liquid Propane Gas
MY	Model Year
NG	Natural Gas
OBD	On-Board Diagnostics
OEM	Original Equipment Manufacturer
ORNL	Oak Ridge National Laboratory
PC	Passenger Cars
PM	Particulate Matter
PN	Particle Number
SBC	Standard Bench Cycle
SDBC	Standard Diesel Bench Cycle
SCR	Selective Catalytic Reduction
SI	Spark Ignition
SRC	Standard Road Cycle
SwRI	Southwest Research Institute
TWC	Three Way Catalyst
UN/ECE	United Nation Economic Commission for Europe
US	United States (of America)
UT	University of Tennessee

LIST OF TABLES AND FIGURES

1 BACKGROUND

In order to reduce pollution caused by road vehicles, Europe introduced the first emission standards for Light-Duty Vehicles (LDV) in 1970 (Directive 70/220/EEC) and in 1988 (Directive 88/77/EEC) for Heavy-Duty Vehicles (HDV).

Today vehicle emissions are regulated under the "Euro standards" legislative framework and a specific Regulation addresses carbon dioxide emissions for light duty vehicles [1]. Each "Euro standard" step introduced over the last two decades resulted in increasingly tightened emission requirements that led to the introduction of new engine and after-treatment technologies needed to meet the requirements.

The Euro 1 (Directives 91/441/EEC, 93/59/EEC) standards applied to passenger cars and light trucks and basically forced the use of catalytic converters and electronic fuel injection systems in vehicles equipped with positive-ignition (PI) engines. Euro 2 (Directives 94/12/EC, 96/69/EC) lowered the applicable emission limits for light duty vehicles. As a result, diesel oxidation catalysts (DOCs) became common in diesel vehicles in order to reduce emissions of unburned hydrocarbons, carbon monoxide and the organic fraction of particulate matter (PM). DOCs however leave substantially unaffected soot and NOx emissions.

Euro 3-4 (Directive 98/69/EC and 2003/76/EC), modified the test cycle by including the cold start, added NOx-specific limits besides combined HC+NOx limits and on-board diagnostics (OBD) requirements for gasoline, LPG, NG and diesel vehicles.

Due to the continuous growth of the European diesel vehicles fleet, Euro 5 (Regulations 715/2007 and 692/2008) mainly focused on particulate matter from diesel cars. Euro 5 Regulation introduced for the first time an emission limit on particle number (PN, #/km) for compression ignition engines, complementing the already existing mass-based limit (PM, mg/km) which was lowered. The new provisions forced de-facto the use of diesel particulate filters (DPFs) to comply with the new standards for PM and PN. Starting from 2014, Euro 6 will lower the limit for NOx emissions from diesel engines (i.e., 80 mg/km, close to the 60 mg/km limit for petrol engines); moreover, the same PN emission limit for diesel vehicles ($6*10^{11}$/km) will apply in 2017 to direct injection gasoline vehicles in order to control the particle emissions of this technology that is expected to become more popular in the near future. Compared to Euro 5, a major change in the after-treatment technology applied to light duty diesel vehicles is expected as a consequence of the stricter NOx limit and of the development of a procedure to control real driving emissions. It is not fully clear yet what technology will be the preferred one but SCR and LNT are the most likely to be adopted to control NOx emissions in lean burn engines.

New vehicle standards are only beneficial in terms of air quality improvement to the degree that they effectively reduce pollutant emissions during the actual vehicle use. This implies compliance with emissions standards not only at type approval or when the vehicle comes off the assembly line but also under real-world driving conditions and throughout its useful life [2]. For this reason durability requirements, already introduced by the previous Euro steps, were significantly extended with the Euro 5-6 standards (Regulation EC 692/2008 implementing and amending Regulation EC 715/2007) [3]. The minimum mileage over which passenger cars and light commercial vehicles should comply with the emission standards was indeed extended from 80,000 km (requirement in force up to Euro 4) to 160,000 km. As far as the durability demonstration procedure is concerned, next to the whole vehicle mileage accumulation approach, the possibility of using deterioration factors (DFs) was maintained and integrated with accelerated ageing procedures and new provisions that take into consideration the technical progress of the vehicles.

EC Regulation 715/2007

on the type approval of motor vehicles with respect to light passenger
and commercial vehicles (Euro 5 and Euro 6) and on access to vehicle repair and maintenance information

ANNEX VII
VERIFYING THE DURABILITY OF POLLUTION CONTROL DEVICES
(TYPE 5 TEST)

"1. 1 This Annex describes the tests for verifying the durability of pollution control devices. The durability requirements shall be demonstrated using one of the three options set out in points 1.2, 1.3, and 1.4."

The steady growth in freight transport by truck required the introduction of dedicated emission standards for heavy-duty vehicles.

First Euro I and Euro II standards (Directive 88/77/EEC) applied to both truck engines and urban buses. With the adoption of Directive 1999/96/EC in 1987, Euro III and Euro IV/V standards were set together with voluntary, more stringent, emission limits for extra low emission vehicles (known as "enhanced environmentally friendly vehicles", or EEVs). The amended Euro IV-V standards (Directive 2005/55/EC) introduced durability and OBD requirements and restated emission limits. As for LDV, accelerated ageing or the application of DFs may also be used to verify the durability of after-treatment systems.

The adoption of more stringent PM and NOx limits with the Euro IV and Euro V standards, resulted in the implementation of different technologies compared to LD vehicles, for which the use of DPFs was the preferred choice. This was mainly due to the fact that in the HD sector fuel economy and fuel-related costs are among the most important factors for the competitiveness of transport companies. As a result, manufacturers preferred to tune HD engines to maximize fuel economy and, in terms of pollutant emissions, this means low PM and high NOx engine-out emissions. Adopting this strategy and by means of selective catalytic reduction devices (SCR), it was in general possible to comply with both NOx and PM standards without the use of DPFs.

The most recent Euro VI standards (Regulation EU 582/2011 implementing and amending Regulation EC 595/2009) [4] came into force in January 2013 for new type approvals (2014 for all registrations) and introduced particle number (PN) emission limits, stricter OBD and durability (e.g. useful life extended from 500,000 to 700,000 km for the heaviest vehicles category) requirements as well as provisions for off-cycle and in-use conformity testing. The introduction of a particle number limit for heavy-duty engines will force the adoption of DPFs also for this vehicle category. With the introduction of Euro VI and Euro 6 standards it is expected that the after-treatment technologies for light-duty and heavy-duty diesel vehicles will converge, for many applications, on the typical configuration "oxidation catalyst+SCR+DPF". [46]

2 DETERIORATION MECHANISMS FOR DIFFERENT AFTER-TREATMENT DEVICES

With increasingly stringent emission standards, advanced after-treatment devices are expected to play a major role also for diesel vehicles. The durability of the after-treatment systems can be verified through mileage accumulation tests, i.e., by driving vehicles over the required distance (i.e., 160,000 km in case of Euro 6) and verifying the emissions performance afterwards. Economic constraints on one side and the need to reduce development time on the other, require however the development of cheaper and less time consuming alternative procedures compared to the full mileage accumulation [5]. To identify appropriate alternatives, a detailed understanding of the ageing processes relevant for the specific after-treatment devices is essential.

The efficiency of catalysts and particle filters decreases as a consequence of the following main ageing mechanisms [5]-[8], with different intensity and different sensitivity depending on chemical substances and exhaust temperatures:

- *Mechanical/physical degradation*, consisting in physical modification of the device caused by
    - Plugging, mainly due to lubricant-derived ash deposition. Ash accumulates in the filter over extended use and alters its geometry (ash deposits in the form of a layer on the filter walls and/or a plug at the back of the filter channels), reducing the filter volume and increasing filter's pressure drop. Deposition of soot from incomplete regeneration can also contribute to filter plugging. In the case of catalysts, soot and ash residues cover the active surface (pore plugging) deteriorating the catalyst performance.
    - Cracking, due to mechanical or thermal stress. This may lead to loss of catalytic material/internal surface area due to structural alterations for catalysts, or reduction of the filtration efficiency in case of filters.
- *Chemical deactivation*, mainly due to lubricant oil additives (phosphorus, zinc and calcium) and sulphur while other contaminants contained in the fuel play usually a minor role because of their very low concentration; the catalyst active surface is deteriorated through
    - catalyst site poisoning (irreversible adsorption, deposition or reaction),
    - competitive, reversible adsorption of poison precursors (inhibition)
    - physical/chemical blocking of pores (via soot or metal deposition on the internal pore structure of the catalyst)
- *Thermal deactivation*, occurs at high temperatures and is related to the catalyst active surface degradation caused by
    - sintering of noble metal particles (loss of active surface via actual structural alteration of the catalyst)
    - sintering and phase alterations of the compounds that form the washcoat

Appropriate accelerated ageing methods can be defined only if the deactivation and deterioration mechanisms of the specific after-treatment system are sufficiently known. An overview of the main deterioration mechanisms for the most commonly used after-treatment technologies will be given in the following sections.

2.1 THREE WAY CATALYST (TWC)

Abatement of pollutants from gasoline engines is successfully accomplished by means of three way catalysts (TWC) which catalyses the reactions between oxidizing (O_2 and NOx) and reducing (CO and HC) species present in the exhaust [9]. This device takes its name from the three simultaneous tasks fulfilled: reduction of nitrogen oxides to nitrogen and oxygen, oxidation of carbon monoxide to carbon dioxide, oxidation of unburnt hydrocarbons to carbon dioxide and water.

Most current TWCs consist of a catalyst support or substrate (generally a ceramic monolith with a honeycomb structure) where the different active phases are loaded. These active phases are mainly composed of noble metals (e.g. platinum, palladium and rhodium), cerium-based oxides and alumina [9]. The active phases are loaded onto the substrate as a thin layer (referred to as washcoat), typically 10-150µm thick. The washcoat is a carrier for the catalytic materials and is used to disperse the materials over a large surface area. Aluminum oxide, titanium dioxide, silicon dioxide, or a mixture of silica and alumina can be used. The catalytic materials are suspended in the washcoat prior to applying to the substrate. Washcoat materials form a rough, irregular surface, which greatly increases the surface area compared to the smooth surface of the bare substrate.

TWC performance degradation can be mainly due to thermal deactivation or chemical deterioration. Thermal deactivation occurs at high temperatures, starting between 800 and 900°C (or even below, depending on the catalyst composition[1]). It consists in the degradation of the active surface caused by sintering of noble metal

---

[1] Substantial sintering of platinum occurs on alumina supports at temperatures greater than 600°C, but on ceria-alumina supports the re-dispersion of noble metals is stabilised up to 800°C. Thermally-induced changes in the washcoat mainly consist in surface area loss, mainly due to phase transformation of γ-alumina, which is not expected below 900°C [6].

particles and/or sintering and phase alterations of the compounds that form the washcoat. This phenomenon depends on the composition of the washcoat (the use of special compounds can increase metals and alumina thermal stability) and is strongly aggravated by exhaust gas property changes (high temperature gradients can damage the substrate and impact washcoat adhesion) [5].

Chemical deactivation results in the degradation of the active surface through: catalyst site poisoning (irreversible adsorption or reaction), competitive reversible adsorption of poison precursors and physical/chemical blocking of pores. In the case of three-way catalysts, lubricant oil additives represent the main source of chemical deactivation in modern engine. Contaminants such as phosphorus, zinc and calcium are deposited on the catalyst surface, blocking the active sites. Another important contaminant is sulphur present in the fuel and in the lubricant. However the sulphur content of the fuel does not represent any more a problem in the EU where ultra-low sulphur fuels are used, but is an important concern in other areas.

Generally speaking, thanks to the reduction in oil consumption of modern engines and improvement in fuel quality, chemical poisoning of TWC has been significantly reduced. Thermal ageing, with particular reference to sintering of noble metal particles, is the major pathway for the deactivation or malfunction of TWCs.

2.2 DIESEL OXIDATION CATALYST (DOC)

An oxidation catalyst is a flow through exhaust device that consists of a honeycomb structure covered with a layer of chemical catalyst. This layer contains small amounts of precious metal -generally platinum or palladium- that interact with and oxidize pollutants in the exhaust stream by oxygen (present in large quantities in diesel exhaust), thereby reducing poisonous emissions.

In the after-treatment of exhaust gases, they currently play two primary roles: oxidizing HC and CO emissions (either reducing engine emissions or burning fuel to actively regenerate a DPF), and generating NO_2 for passive DPF regeneration and/or enhance SCR deNOx reactions, particularly at low temperatures [10][11]. The aging of DOCs is critical not only because of its direct effect on HC and CO emissions control but also as it may affect DPF regeneration and SRC performance.

The DOC is generally placed next to the engine in order to rapidly reach light-off temperature and start the catalytic oxidation of CO and HC during cold-start conditions. Due to such positioning, the oxidation catalyst is directly exposed to high temperatures, engine-out soot, lubrication oil ash and sulphur dioxide emissions.

Studies performed on aged catalysts [11]-[14] reports that the primary mechanisms of DOCs deactivation are thermal ageing and ash deposits. It has been shown that samples taken from the front part of the catalyst exhibited significant ash deposition while samples taken from the rear part of the catalyst were generally thermally aged. The overall light-off characteristics of the catalyst typically deteriorates due to both effects as the mileage increases [11]. In addition soot and hydrocarbons can cover the active sites of the catalyst in certain operating modes, leading to a considerable increase of light-off temperatures; the resulting DOC degradation is usually reversible and oxidation performance after soot removal (in a high-temperature oxidizing environment) is observed to be comparable to that of a fresh catalyst under the same testing conditions [12]. Phosphorus poisoning is shown to have minimal effect on DOC performance deterioration. The effect of sulphur, which mainly consists in a reversible poisoning, has been strongly reduced by the use of ultra-low sulphur fuels in Europe.

2.3 SELECTIVE CATALYTIC REDUCTION (SCR)

SCR catalysts are manufactured from various ceramic materials used as a substrate, such as titanium oxide, and active catalytic components. Active catalytic components are usually oxides of base metals, (vanadium pentoxide, V_2O_5, molybdenum trioxide, MoO_3, and tungsten trioxide, WO_3), zeolites, or various precious metals, depending on the temperature application range (see **Table 1**).

Table 1: SCR catalyst technologies [14]

Catalyst	Temperature Range, °C
Platinum (Pt)	175 - 250
Vanadium (V_2O_5)	300 - 450
Zeolite, high temperature (Fe)	350 - 600
Zeolite, low temperature (Cu)	150 - 450

Besides the main technologies used (Vanadium and Zeolite based SCR), a wide variety of SCR-materials have been investigated (e.g. the Ti-based catalysts, the Ag-Al_2O_3 compounds, but also the Fe-containing zeolite based catalysts [16]). Of course the catalyst material determines the SCR performance as well as the aging mechanisms.

The term Selective Catalytic Reduction is used to describe a chemical reaction in which nitrogen oxides (NOx) in diesel exhaust gas are converted into water (H_2O) and nitrogen (N_2). Thanks to the SCR, especially if used in combination with internal engine technologies such as exhaust gas recirculation (EGR), extremely low nitrogen oxide emissions can be achieved. This system uses ammonia as reducing agent. In general ammonia is obtained by the thermal degradation of urea that is sprayed into the exhaust flow upstream the SCR catalyst.

While in typical heavy-duty configurations the SCR catalyst is positioned downstream of the DPF, in light-duty applications the SCR may be either placed downstream of the particle filter or upstream (especially in the case of DPFs using fuel born catalyst). In the latter case the SCR would experience exposure to more metal impurities and higher temperatures [17]. Of course, if the SCR is located downstream the DPF, it will be much less exposed to ash coming from the engine but would be exposed to the high temperatures generated during DPF regeneration. Different exhaust system combinations have been proposed [18] with different SCR locations. For example, in the case of a combined DOC-DPF catalysed-filter layout, the SCR is placed under-floor and downstream of the catalysed filter, thus entailing high heat loss. A combined SCR-DPF, located downstream of the DOC, reduces heat loss between DOC and SCR-DPF during regeneration. However, the high temperatures occurring during regeneration potentially weaken SCR durability. The SCR exposure to hot exhaust gas over a period of time results in a decrease of catalyst reactivity due to sintering (thermal deactivation), ash plugging/masking (physical deactivation) and poisoning (chemical deactivation), the latter depending on the type of fuel burned and the combustion environment. New SCR catalyst formulations and designs are improving both low and high-temperature performance, as well as reducing the sensitivity to hydrocarbon and sulphur poisoning [10]. Experimental evidence [16][19] showed that carbonaceous deposits, hydrocarbons and N containing species can be removed from the surface of SCR catalysts by heating it under oxidative conditions resulting in a (partial) recovery of the catalyst activity. The type of lubricating oil used in the internal combustion engine might be an important factor in the deactivation of the catalyst. Exposure to metal impurities [17] only affected SCR reactivity in the first centimetres of the catalyst and may not compromise compliance with emission limits.

2.4 LEAN-NOX TRAP (LNT)

The LNT, also known as NOx adsorber, could represent the preferred deNOx option for small lean-burn (diesel and direct injection gasoline) passenger cars and is of interest in small vehicles with limited space or in which the use of urea is difficult [11].

The LNT technology combines three active components: the oxidation catalyst (e.g. platinum), the adsorbent (barium and/or other oxides), and the reduction catalyst (e.g. palladium or rhodium). The adsorbents, which are incorporated into the catalyst washcoat, chemically bind NOx during lean engine operation ($\lambda>1$, where λ is the air to fuel ratio during combustion). When the adsorbent capacity is saturated, the system is regenerated during a period of rich engine operation ($\lambda>1$), and the released NOx is reduced to nitrogen (N_2) over the catalyst.

Sulphur poisoning, thermal degradation and carbon deposition are the primary deactivation mechanisms that affect the efficiency of LNT catalysts [6][20]. In typical lean exhaust, sulphur is mainly present in the form of SO_2, which can poison not only the basic NOx trapping component but also the metal oxide support. In addition, during rich operating conditions, sulphur can also accumulate on the precious metal component, and therefore decrease its NOx reduction and the following NO oxidation activities remarkably. Therefore, periodic desulphation is necessary to remove sulphur from the catalyst surface and recover satisfactory catalyst performance. The desulphation is generally carried out at high temperature (>600°C) under rich conditions. However, this high temperature treatment is the major causes of thermal degradation of LNT catalysts. In addition, during a rich-burn cycle, the oxidation of hydrocarbon, CO and H_2, generates heat at the catalyst surface and results in thermal degradation as well. Carbon deposition on Platinum sites by the decomposition of CO and hydrocarbons is another deactivation mechanism that may lead to a progressive decay in catalysts performance.

Experimental evidence [21]-[23] demonstrated that changes of the physical and chemical catalyst properties caused by lean/rich ageing conditions significantly differ from those produced by lean hydrothermal ageing.

2.5 DIESEL PARTICULATE FILTER (DPF)

A DPF is a device designed to remove diesel particulate matter or soot from the exhaust gas of a diesel engine. In the most common type – wall-flow filters – particulate matter is removed by physical filtration using a honeycomb structure (made of ceramic materials, e.g. cordierite, silicon carbide or aluminium titanate) with the channels blocked at alternate ends. The exhaust gas is thus forced to flow through the walls between the channels and the particulate matter is deposited on the walls [23]. Wall-flow diesel particulate filters usually remove 85% or more of the soot, and under certain conditions can attain soot removal efficiencies approaching 100%. Since the continuous deposition of soot into the filter would eventually block it, it is necessary to restore suitable filtration efficiency by burning-off the collected particulate on a regular basis. This process is known as regeneration. Regeneration can be active, when triggered by the ECU and achieved by artificially increasing the exhaust gas temperature (e.g with a post-injection of fuel), or passive, when the soot is removed by means of chemical reaction with NO_2 or when the temperature of the exhausts reaches high values as a consequence of high loads. Diesel particulate filters (DPFs) have been in commercial production for original equipment manufacturer (OEM) application for more than 10 years, but filters optimisation activity is still on-going [11]. Even if durability requirements are set at 160,000 km by the current EU emission standards for LDVs [3], the trend is to focus on "fit-for-life" solutions rather than DPF servicing (ash removal) during the vehicle lifetime [25]. Field experience about DPF durability exists, as a large number of OEM vehicles equipped with DPFs is approaching the end of their useful life in Europe; on the other side, very limited data about DPF bench ageing have been published.

The most significant DPF durability issues are related to the regeneration phase (physical integrity) and to lubricant oil ash accumulation (plugging) [27]:

- Physical Integrity
    - Thermal Crack (from uncontrolled regeneration)
    - Mechanical Crack (due to vibration/defective canning)
- Plugging
    - Soot (from incomplete regeneration)
    - Ash (primarily from lubricant oil)

Excessive soot accumulation in the filter would also lead to a rapid increase of backpressure, affecting engine functioning and may force, in extreme cases, engine shut down. One of the most serious problems concerning system's durability is the performance deterioration due to ash particles accumulation [26]. Ash particles depositing along the channels wall or at the channels plug continually decrease the effective diameter and length of exhaust gas channels, unless the filter is removed from the vehicle and cleaned. As a consequence, the filter's soot storage capacity is reduced; the modified flow conditions through the filter also alter the distribution of the accumulated soot and affect the filter's pressure drop sensitivity and regeneration process.

Thermal degradation and poisoning (from sulphur, phosphorus and others) of regeneration catalysts are also known to potentially affect filter durability [27][28].

2.6 GASOLINE PARTICULATE FILTER (GPF)

After the introduction of an emission limit on particulate mass for PI direct injection engines with the Euro 5 standard, next Euro 6b / 6c will additionally set limits on their emissions in terms of particle number. The automotive industry is currently evaluating particulate filters as a potential technology to reduce particle emissions from gasoline direct injection (G-DI) engines [29]-[41], as they proved to be very efficient in controlling particle number emissions from diesel vehicles. Several approaches are considered for installation of the GPF in the exhaust system, but they can be classified into two main options [29]: a) close coupled to the engine or b) under floor installation. A close coupled GPF will most probably also incorporate some catalytic coating thus acting as a four way catalyst. Under floor installations may or may not incorporate catalytic activity.

Exhaust gas from G-DI engines is characterized by much lower particle concentrations compared to diesel engines [33]; therefore much lower soot accumulation in the GPF takes place. Recent studies [30]-[31] showed that soot accumulation is not significant even after prolonged operation under real-world driving conditions. Consequently, no extreme heat release due to soot oxidation is expected so thermal durability is not considered an issue by substrate manufacturers [29]. Excessive soot accumulation was only observed under repeated start-stop operation at sub-zero ambient temperatures [30]. The low level of soot loading allows for the use of a more compact, less expensive filters configuration compared to DPF. The size optimisation will more likely depend on the requirements for ash storage capabilities, since ash emissions are expected to be higher in gasoline vehicles due to the relatively higher engine speeds [35]. Dedicated studies performed by car manufacturers did not reveal significant ash accumulation or any performance deterioration for the GPFs examined [29], but further investigation is required on this issue.

A summary of primary deactivation mechanisms for after-treatment devices discussed above is provided in **Table 2** below.

Table 2: Most critical deterioration mechanisms

AFT Device	Thermal Deactivation	Chemical Poisoning	Physical	
			Plugging	Cracking
TWC	++	-	-	-
DOC	++	-	+ Ash	-
SCR	++	-	+ Ash	-
LNT	++	+ Sulphur	+ Ash	-
DPF	-	-	++ Ash & Soot	+
GPF	?	-	++ Ash	?

LEGEND: ++ primary, + average, - minor, ? no info available in the literature.

3 EXPECTED EVOLUTION OF AFTER-TREATMENT TECHNOLOGIES FOR EURO 6 PASSENGER CARS

The introduction of the new Euro 6 standards will have a major impact on the after-treatment strategies to be adopted in Euro 6 LD vehicles to meet the emission limits.

In the previous chapter, particulate filters have been presented as a potential technology to reduce particle emissions from gasoline direct injection (G-DI) engines as required by the new Euro 6 emission standard. As stated by recent studies [43], it is very likely that gasoline particulate filters (GPF) will not need active regeneration strategies, as several passive regeneration opportunities will take place during mixed operation:

- Fuel shut-off: Causes a short-term dramatic enleanment and increase in exhaust temperature leading to soot combustion;
- Lean spike: Originates a short-term increase in air-to-fuel ratio (AFR) leading to soot combustion;
- Prolonged high speed cruise/high temperature operation: Leads to continuous regeneration, thanks to the prolonged elevated exhaust temperatures and the oxygen available in the exhaust under these conditions.

The many opportunities for soot combustion during normal operation together with the lower engine-out levels of soot compared to diesel vehicles and relatively low PN engine-out emissions, will allow for more open GPF structures with lower efficiencies compared to DPFs. In conclusion, ageing mechanisms of after-treatment devices of Euro 6 gasoline vehicles with a GPF are likely to not differ too much compared to vehicles equipped with a TWC only. The only potential new issue is the accumulation of ash coming from the lubricant in the GPF. The situation is clearly different in the case of a gasoline car equipped with a lean burn engine using a LNT system for which the desulphation event may play an important role.

When considering diesel Euro 6 light duty vehicles, the exhaust gas after-treatment system is expected to include oxidation catalysts, particulate reduction devices (DPF) and NOx reduction devices (LNT, SCR, SCRF – i.e. the SCR on Filter).

The NOx control strategy that will be adopted will influence remarkably the amount of NO_2 available for passive regeneration of DPFs.

There are four possible technology scenarios for NOx reduction:

- LNT: Placed upstream the DPF, it will reduce the NO_2 available for passive regeneration. This may lead to more frequent active regenerations of the DPF.
- SCR: Generally placed downstream the DPF, does not change or even increases the NO_2 available for passive regeneration of DPFs;
- SCRF: This is a system in which the DPF and the SCR are combined together. NO_2 preferentially reacts with ammonia and therefore it is not available for passive regeneration.
- No NOx after-treatment or only EGR: A reduction of the NO_2 available is expected especially under legislative testing conditions – less under real driving conditions.

Therefore, only vehicles equipped with SCR will experience appreciable opportunities for DPF passive regeneration, while active regeneration will be generally needed for the other solutions described. It is likely that in many applications this will lead to more frequent active regeneration.

Moreover, the change in engine-out NOx and soot levels for Euro 6 vehicles has brought recent developments in DPFs materials and regeneration strategies. Almost all DPFs are now downsized and placed in a close-coupled position, with higher porosity to reduce engine backpressure impact on fuel economy. The effect of reducing the DPF size, together with lower soot loading capabilities of new substrate materials and higher engine-out soot level will also result in more frequent DPF regenerations (~100km interval in extreme cases).

In conclusion, it is likely that new diesel vehicles will have more frequent active regenerations compared to Euro 4/5 vehicles. Clearly, this will have an impact on durability performance of the after-treatment system as well as on accelerated ageing procedures.

If a Fuel Borne Catalyst (FBC) is used to promote the DPF regeneration, the configuration of the after-treatment system is expected to be different compared to DPFs not using the FBC. The FBC is a metallic additive that is burnt with the fuel in the engine and is bound to soot particles that accumulate in the DPF. The FBC catalyses the reaction of soot with oxygen in the exhaust gas by lowering the temperature at which soot burns (from over 600°C to around 350°C depending on engine emissions) [44]. As a consequence, passive regeneration occurs with higher frequency during normal operation and active regeneration can be achieved at lower temperatures [45]. A disadvantage of fuel borne catalyst is the increased accumulation of metal ash in the filter [46]. The fact that the FBC reduces the regeneration temperature allows placing the

DPF farther away from the engine and more specifically downstream of the SCR. An SCR placed upstream of the DPF and closer to the exhaust manifold will be exposed to higher temperatures with the possibility of achieving very high NOx conversion efficiency and potentially better fuel economy. However this means also that thermal ageing may be more important in this case and that the SCR will be exposed to more ash coming from the engine.

4 CURRENT EUROPEAN ACCELERATED AGEING PROCEDURE

UN/ECE Regulation No. 83 [42] establishes uniform provisions concerning the approval of vehicles with regard to the emission of pollutants. These provisions reflect the European Regulations 715/2007 and 692/2008 [3]. In total, six types of tests are prescribed, among which the Type V test has the purpose to verify the compliance with the durability requirements for after-treatment systems (160,000 km for all PI and CI LDVs).

The durability of these systems should be verified using one of the following three options (see Annex VII in Regulation 692/2008 [3]):

1. WHOLE VEHICLE DURABILITY TEST: Consists in a mileage accumulation of 160,000 km, conducted by driving the vehicle on a test track, on the road, or on a chassis dynamometer (whole vehicle mileage accumulation);

2. BENCH AGEING DURABILITY TEST: Two different procedures are defined depending on the engine technology (PI or CI engines). The purpose of these procedures is to achieve an equivalent ageing compared to the whole vehicle durability test but in a much shorter time (accelerated ageing).

3. DETERIORATION FACTORS: Consists in applying assigned deterioration factors at the type approval emission tests (DFs) (Annex VII, Paragraph 1.4 in Regulation 692/2008 [3]; see also Section 0). Upon request of the manufacturer, assigned DFs may be replaced with those measured for the whole vehicle or during a bench ageing durability test.

A more detailed description of the three options for durability testing will be provided in the following sections.

4.1 WHOLE VEHICLE DURABILITY TEST

According to the current European legislation [4], a first method to demonstrate the durability of the emission control system is to run a vehicle for 160,000 km following the US-EPA AMA (Approved Mileage Accumulation) cycle (11 laps/6km each) or the Standard Road Cycle, SRC (7 laps/6km each). The cycle is repeated until the vehicle has covered a minimum distance of 160,000 km; the vehicle may be run on the road, on a test track, or on a mileage accumulation dynamometer.

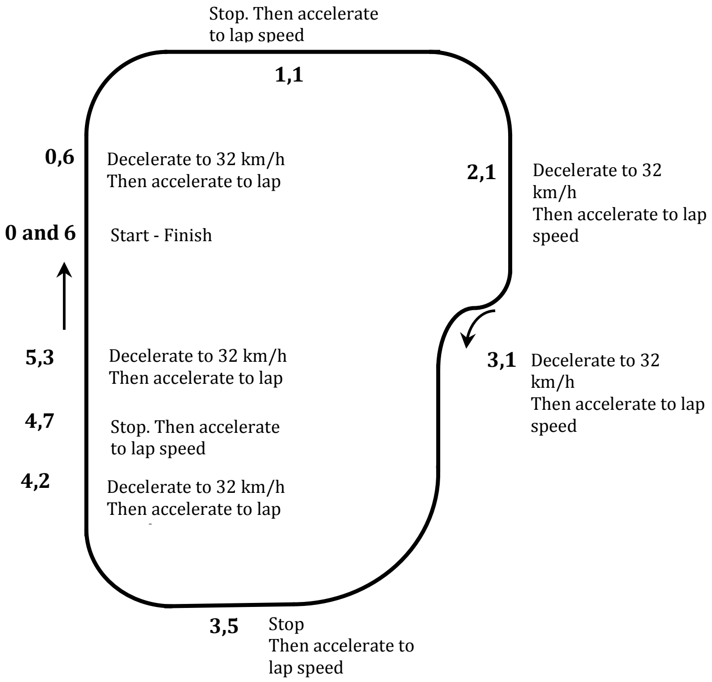
Both the AMA cycle and the SRC cycle are currently allowed but, as it will be shown later, the AMA cycle is considered obsolete. In addition, due to the lower average speed it takes longer to cover 160000 km compared to the SRC.

The candidate vehicle shall be in good mechanical order, equipped with new engine and antipollution devices; it may be the same as that presented for the Type I Test (verifying average exhaust emissions at ambient conditions for type-approval).

Maintenance and adjustments shall be implemented as recommended by the manufacturer. The fuel used shall be suitable for the engine and commercially available.

Operating cycle, AMA (Figure 1)

- Average speed 66.4 km/h
- Cycles 1÷9: The vehicle is stopped four times, with the engine idling each time for 15 seconds;
- Normal acceleration and deceleration;
- Five decelerations in the middle of each cycle, followed by gradual acceleration again;
- 10th cycle at a steady speed of 89 km/h;
- 11th cycle with 2 maximum accelerations from stop point up to 113 km/h.



Cycle	*Speed*
1	64
2	48
3	64
4	64
5	56
6	48
7	56
8	72
9	56
10	89
11	113

Figure 1: Driving schedule and maximum speed at each AMA operating cycle [42].

Standard Road Cycle, SRC (Figure 2)

- Average speed of 74.5 km/h;
- Maximum cruise speed is 128 km/h;
- Acceleration rates range from light to hard accelerations; most accelerations are moderate and there are no wide-open-throttle accelerations;
- 24 fuel-cut decelerations;
- Deceleration rates range from coast-down (no brake force applied) to moderate.

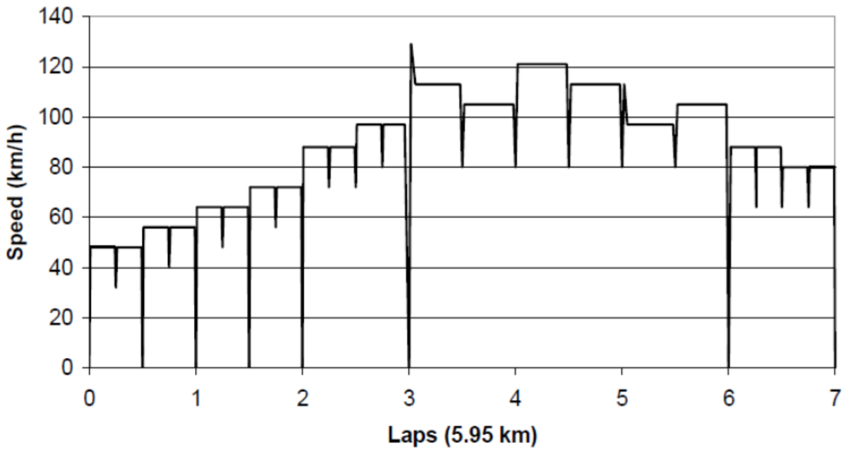


Figure 2: Standard Road Cycle (SRC) [3].

Differences between the SRC and the AMA cycles

Before the introduction of the SRC cycle, the EPA durability demonstration method was based on the AMA cycle as a whole vehicle mileage accumulation cycle.

Concerns about the inadequacy of any fixed cycle - including the AMA cycle - to accurately approximate in-use deterioration, together with the high costs of the mileage accumulation process, led to the conclusion that the AMA cycle had become obsolete.

The AMA cycle was developed before vehicles were equipped with catalytic converters. It contains a substantial portion of low-speed driving, designed to address concerns about engine deposits. While engine deposits were a major source of emissions deterioration in pre-catalyst vehicles, the advent of catalytic converters, better fuel quality and advanced fuel injection systems shifted the causes of deterioration from low-speed driving to driving modes that cause elevated catalyst temperatures, e.g., high speed/load regimes. The AMA driving cycle does not properly capture such driving modes. This makes the process longer but adds little benefit in predicting emission deterioration [59]. In response to these concerns and to ensure the fulfilment of the updated durability objective[2], EPA developed the SRC cycle. The new driving cycle is characterized by operating conditions that are more severe than the average ones observed on the road. The objective was to effectively cover 90 percent of the distribution of emission deterioration rates that occur across the entire fleet of in-use vehicles.

Table 3 shows how the share of high speed driving conditions, which are most critical for thermal ageing, is increased by nearly three times in the SRC compared to the AMA cycle. Moreover, both maximum and average speeds are considerably higher for the SRC (by 13% and 12% respectively) than the AMA cycle.

Table 3: Comparison of SRC and AMA durability cycles

Cycle	Speed distribution				Features			
	Idle	>50 km/h	50-100 km/h	>100 km/h	Max Speed [km/h]	Av. Speed [km/h]	Duration [s]	Distance [km]
SRC	5%	14%	55%	26%	128	74.5	2054	41.4
AMA*		18%	73%	9%	113	66.4	4546	66

* Lap speed distribution not considering acceleration and deceleration.

---

[2] "The durability program must predict an expected in-use emission deterioration rate and emission level that effectively represents a significant majority (approximately 90 percent) of the distribution of emission levels and deterioration in actual use over the full and intermediate useful life of candidate in-use vehicles of each vehicle design which uses the durability program"[59].

Figure 3 and **Figure 4** demonstrate how the different speed profiles of the SRC and AMA cycles affect the exhaust gas temperature of a Euro 5 car. It is clear that with the SRC cycle the catalyst spend longer time at higher temperatures than with the AMA cycle.

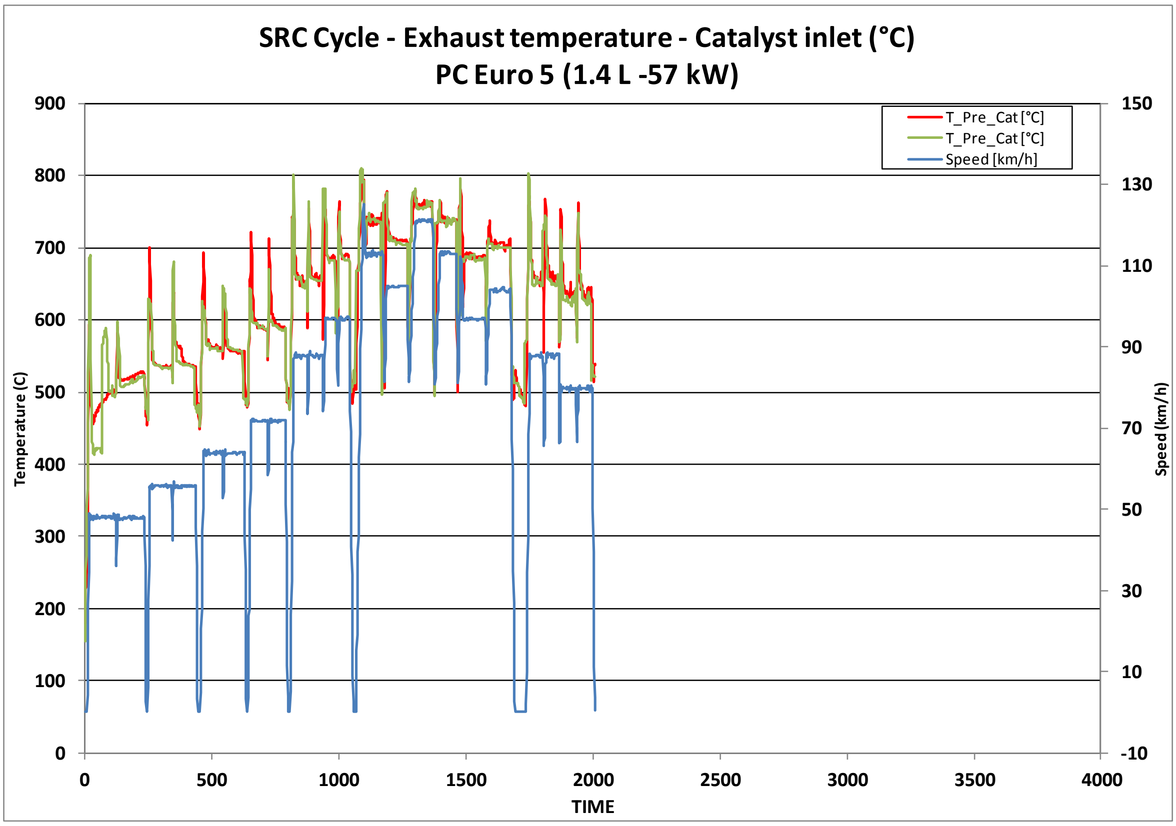


Figure 3: SRC Cycle: measured speed and exhaust temperature for a Euro 5 PC.

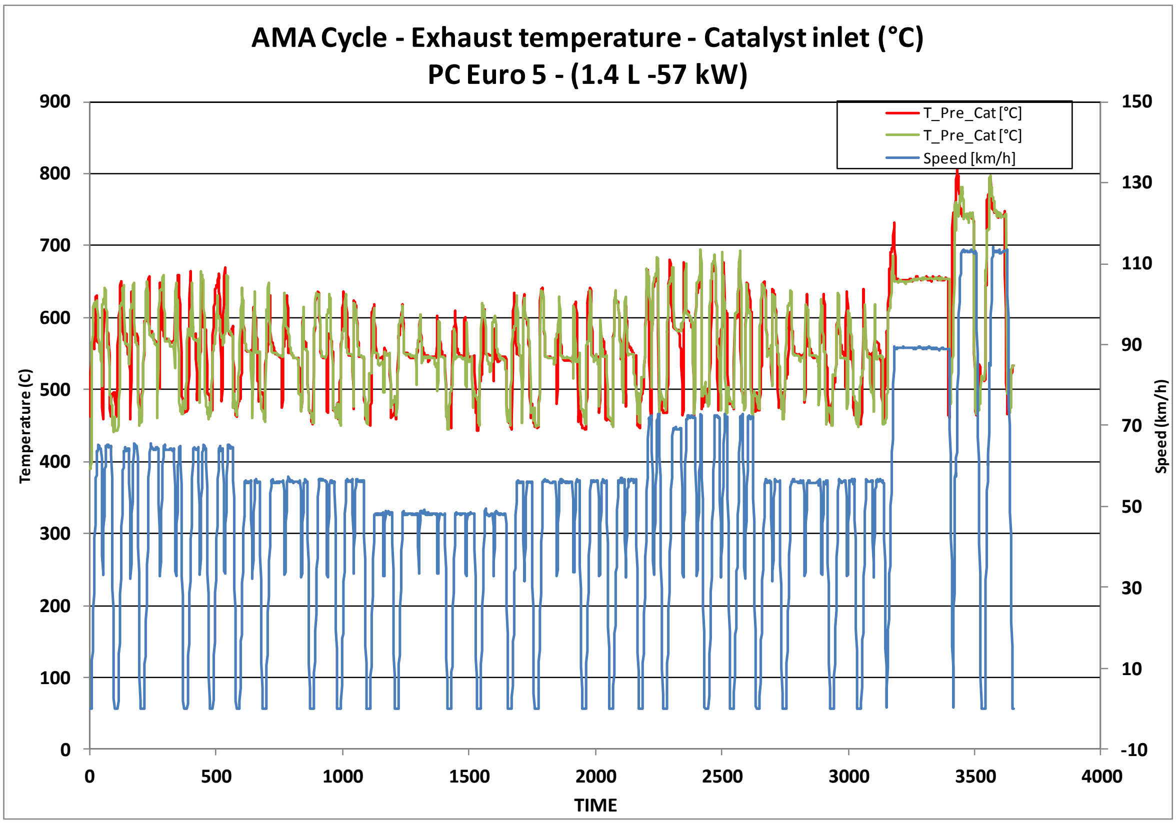


Figure 4: AMA cycle: measured speed and exhaust temperature for a Euro 5 PC.

4.2 ACCELERATED BENCH AGING PROCEDURE

The effect of heat on the efficiency of the catalyst is cumulative, and increases exponentially with rising temperature. Based on this principle, it is possible to reproduce the thermal load on the catalyst over its useful life by exposing it to an appropriate elevated temperature over a shorter period. In this way the full mileage accumulation process can be replaced with an accelerated ageing test.

However, other deterioration mechanisms of after-treatment devices like chemical poisoning, deposit formation, physical stress, etc. cannot be easily and accurately reproduced in a shorter time. In the accelerated bench aging test developed by US-EPA and included in the Euro 5 Regulation, the calculated thermal ageing time needed to reproduce the "real world" thermal load is extended by 10% in order to take into account these other ageing factors. However replacing chemical poisoning with additional thermal aging is only a rough approximation of what occurs in the real world since thermal ageing and other deterioration mechanisms may have completely different impacts on the after-treatment devices. For example, ash contamination is generally limited to the front part of the catalyst and affects mainly light-off characteristics while thermal ageing affects the whole catalyst as well as the overall conversion efficiency.

Table 4 compares the whole-vehicle full mileage accumulation vs. accelerated bench ageing procedures, and summarizes the main advantages and disadvantages of each approach.

Table 4: Advantages and disadvantages of full mileage accumulation and accelerated ageing

WHOLE-VEHICLE MILEAGE ACCUMULATION	ACCELERATED BENCH AGEING
Advantages	
• Road testing reproduces more reliably the 'real-world' aging of after-treatment systems than an engine test. • Mechanisms that influence the deterioration of pollution abatement technologies (thermal ageing, poisoning, coating with fuel impurities, physical deterioration, etc.) are much more correctly accounted for in a road test than in an engine test. • There is no need to adapt the accelerated test procedure to different technologies. • All the components of the pollution abatement devices (sensor, catalyst, engine, etc.) are aged and tested under the same conditions.	• Lower cost. • Shorter time. • Well controlled engine operations. • Higher repeatability of the test procedure and thus better discrimination between results than vehicle testing.
Disadvantages	
• Higher cost and much more time consuming. • More difficult to control driving conditions, especially when driving on test tracks; potentially lower repeatability and reproducibility of tests and a higher variability of test results. • Demanding logistics (long-term availability of a test track or chassis dynamometer) large amount of fuel needed, etc…).	• Accelerated testing could alter the fundamental mechanisms of chemical interactions and physical stress and thereby the observed aging process. • The validation of a new accelerated ageing procedure by means of a correlation between artificially aged systems and systems aged in the field is difficult and resource consuming. • Other factors influencing the catalyst durability (e.g. poisoning, coating with fuel impurities, etc.) may not be adequately accounted for by additional thermal ageing. • Unclear whether all the components of the pollution abatement device are evaluated under the same conditions with the accelerated tests.

Accelerated ageing procedure for vehicles with positive ignition engines

The current European emission legislation [3] defines an accelerated aging procedure for vehicles with PI engines (including hybrid vehicles) using a three-way catalyst as main after-treatment device. The accelerated procedure is taken directly from the US-EPA emission durability rule [59] and consists in ageing a catalyst/oxygen sensor on an ageing bench. The standard bench cycle (SBC) requires the use of an ageing bench with an engine as the source of feed gas for the catalyst. The SBC (**Figure 5**) is a 60-seconds cycle that is repeated as necessary on the ageing bench to reproduce in a shorter time the thermal load on the catalyst recorded over the SRC.

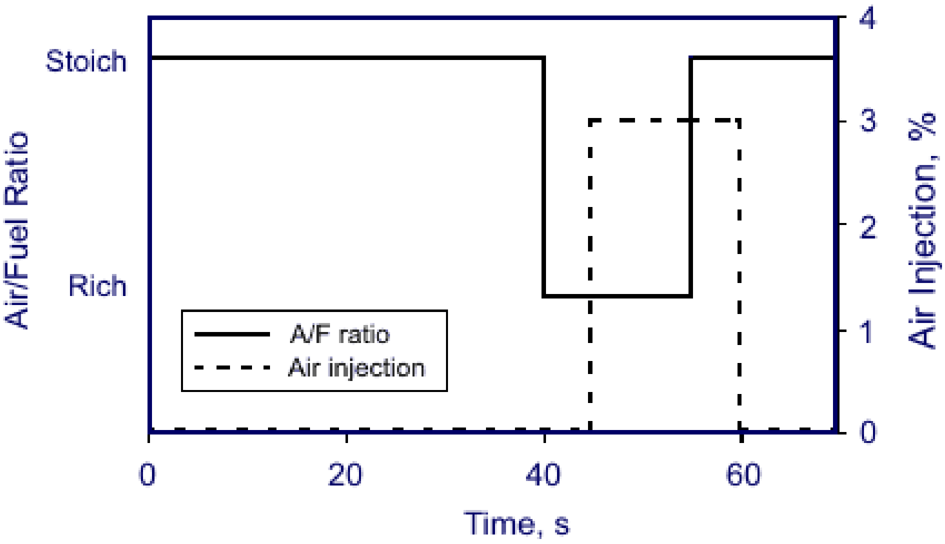


Figure 5: Standard Bench Cycle [3].

The standard bench cycle (SBC) is followed for a period of time calculated from the bench ageing time (BAT) equation as described below.

The BAT equation requires, as input parameters, the catalyst time-at-temperature data measured during at least two full cycles of the SRC. Catalyst temperature shall be measured at a minimum rate of one hertz, and at the location with the highest temperature in the hottest catalyst on the test vehicle. The measured temperature data shall be tabulated into a histogram with temperature groups (bins) of no larger than 25 °C.

For each temperature-bin the equivalent ageing time t_e (in hours) is calculated as follows:

$$t_e = t_h exp\left[R\left(\frac{1}{T_r} - \frac{1}{T_v}\right)\right]$$

Where T_r is the effective reference temperature (in K) which shall be determined for the actual catalyst system design and the actual ageing bench which will be used; T_v is the midpoint temperature (in K) of the considered temperature-bin; R=17,500 is the catalyst thermal reactivity and t_h is the measured time (in hours) within the prescribed temperature-bin adjusted to the full useful life.

The bench ageing time is then determined by summing up t_e over all the temperature groups:

$$BAT = A * \sum t_e$$

Other deterioration sources different from thermal ageing (e.g. chemical poisoning) are taken into account by setting the factor A to the value 1.1. In other words, thermal ageing is increased by 10% to cover other deterioration mechanisms. The BAT provides the equivalent time (in hours) to age the catalyst at the temperature of T_r on the catalyst ageing bench using the SBC to produce the same amount of deterioration experienced by the catalyst due to thermal deactivation over the SRC for 160,000 km.

For calculating deterioration factors at least two Type I Tests before bench ageing of the emission control hardware and at least two Type I Tests after the bench-aged emission hardware is reinstalled have to be performed on the test vehicle. Additional testing may be conducted by the manufacturer. Calculation of the deterioration factors has to be done according to the calculation method specified in Section 4.3.

Accelerated ageing procedure for vehicles with compression-ignition engines

The Standard Bench Cycle (SBC) described in the US-EPA emission durability rule [59] is designed for PI vehicles equipped with a three-way catalyst/oxygen sensor system. The SBC is therefore not applicable to diesel vehicles or other vehicles which do not use a three way catalyst as the main after-treatment emission control device. Consequently, a dedicated accelerated bench ageing procedure was developed in Europe for diesel vehicles, i.e. the Standard Diesel Bench Cycle (SDBC). This is included in the Euro 5 and Euro 6 Regulation [3]. However, the SDBC was included in the legislation upon a proposal of the car industry and at a late stage of the Euro 5 standards development process. At the time the SDBC was not thoroughly assessed and no validation data was presented to support the procedure.

The SDBC is based on the consideration that the regeneration/desulphurization cycles represent the main ageing factors respectively for DPFs and systems that require desulphurisation cycles (e.g. NOx storage catalysts). The standard bench aging procedure requires the installation of the after-treatment system on a dedicated ageing bench with an engine as the source of feed gas for the system. The SDBC shall be run for the period of time calculated from the bench ageing duration (BAD) equation as follows:

BAD = number of regeneration and/or desulphurisation cycles (whichever is the longer) equivalent to 160,000 km of driving

Regeneration intervals shall be measured during at least 10 full cycles of the SRC cycle described above. As an alternative the intervals from the Ki[3] determination may be used. If applicable, desulphurisation intervals shall also be considered based on manufacturer's data.

The ageing bench shall follow the SDBC and deliver appropriate exhaust flow, exhaust constituents, and exhaust temperature to the inlet of the after-treatment system. The SDBC reproduces the engine speed and load conditions that are encountered in the SRC cycle as appropriate to the period for which durability is to be determined.

The manufacturer shall record the number of regenerations/desulphurisations (if applicable) to assure that sufficient ageing has actually occurred.

In order to accelerate the process of ageing, the engine settings on the test bench may be modified to reduce the system (filter or LNT) loading times (e.g., the fuel injection timing or EGR strategy may be modified) and therefore to increase the frequency of regenerations.

Although the determination of the BAD is quite straightforward, how the SDBC should reproduce the engine speed and loads encountered over the SRC is not very well defined. For example, let's assume that during 160,000 km, DPF regeneration occurs every 800 km (peak temperatures lasting ~10 minutes) [17], therefore BAD = 160,000/800 = 200 cycles. This implies that the DPF should be exposed to regeneration events for a total of ~33 hours (=200x10/60).

---

[3] Refer to Ki factors developed by the procedures in section 3 of Annex 13 of UN/ECE Regulation No 83 for type-approval of a vehicle type with a periodically regenerating system.

However, the practical definition of the SDBC characteristics to reproduce engine speed and loads encountered over the SRC is left to the subjective interpretation of the vehicle manufacturer. Likewise, manufacturers can modify engine settings on the test bench to reduce the system loading times. Such degree of freedom left in the definition of the durability procedure for diesel vehicles could result in a variety of durability procedures that might be not fully equivalent to each other.

As for PI engine vehicles, at least two Type I Tests before bench ageing of the emission control hardware and at least two Type I Tests after the bench-aged emission hardware is reinstalled into the vehicle have to be performed in order to calculate valid deterioration factors. Additional testing may be conducted by the manufacturer. Calculation of the deterioration factors has to be done according to the calculation method specified in Section 4.3.

4.3 CALCULATION OF DETERIORATION FACTORS FROM AGEING PROCEDURES

According to UN/ECE Regulation No. 83 [42], exhaust emissions for Type 5 whole vehicle durability test are measured at 0 km and at least every 10,000 km (±400 km) at regular intervals until having covered the complete distance of 160,000 km. For vehicles equipped with periodically regenerating systems, it shall be checked that a regeneration period is not occurring during an emissions measurement, as measured data would not be valid in that case. The emissions results shall be plotted as a function of the running distance, and the best linear regression fits hall be drawn, disregarding data at 0 km.

The acceptability criteria for the calculation of DFs are met if the interpolated 6,400 km and 160,000 km points on the best-fit regression line are within the limits, or if the best-fit line crosses an applicable limit with a negative slope but the actual emissions at 160,000 km are below that limit.

A multiplicative exhaust emission deterioration factor (*MULT DF*) shall be calculated for each pollutant as follows (three decimals are to be used for *DF* and four for *Mi*):

$$MULT\ DF = \frac{Mi_2}{Mi_1} = \frac{mass\ emission\ of\ pollutant\ i\ \left(\frac{g}{km}\right)\ interpolated\ to\ 160{,}000\ km}{mass\ emission\ of\ pollutant\ i\ \left(\frac{g}{km}\right)\ interpolated\ to\ 6{,}400\ km} \geq 1$$

At the request of a manufacturer, an additive exhaust emission deterioration factor (*ADD DF*) shall be calculated for each pollutant as follows:

$$ADD\ DF = Mi_2 - Mi_1$$

From the definition given above, additive and multiplicative DFs can be linked from the following formula [63], as graphically represented in **Figure 6**:

$$ADD\ DF = LIMIT - \frac{LIMIT}{MULT\ DF}$$

Where LIMIT, is the corresponding emission limit (according to relevant emission standard).

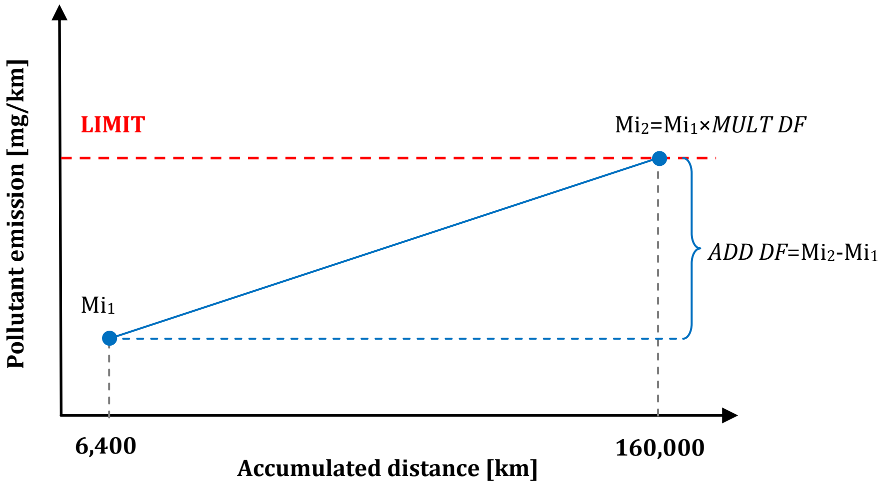


Figure 6: Additive and multiplicative deterioration factor.

5 SUITABILITY OF EU ACCELERATED DURABILITY PROCEDURES FOR EURO 6 AFTERTREATMENT TECHNOLOGIES

5.1 SBC

In the case of positive ignition engines, the accelerated ageing procedure is based on the exposure of the catalysts to higher temperatures for a shorter period of time compared to real world conditions. This is possible since thermal ageing is the predominant deterioration mechanism for three-way catalysts commonly applied to this vehicle category (see **Table 2**).

A more careful evaluation of the durability procedure is required when looking forward to the possible application of GPFs for particle emission control of Euro 6 gasoline vehicles. As discussed in Chapter 3. GPFs are expected to see several passive regeneration opportunities during mixed operation. Therefore active regeneration is expected to play a minor role. This means that the SBC could be still appropriate to reproduce the thermal load over the useful life of the vehicle. However it should be carefully checked whether the foreseen air injection in SBC (see **Figure 5**) would be sufficient to reproduce the passive regeneration opportunities for GPFs.

In case of gasoline engines equipped with a LNT system, the SBC may be not appropriate to reproduce the thermal load experienced during real world driving conditions. At least the time-at-temperature data on the basis of which the equivalent ageing time is calculated should include the peak temperatures experienced during the desulphation procedures.

Finally, chemical poisoning is taken into account by extending the equivalent ageing time by 10%. However, ash deposition may play a different role in case a GPF is present compared to vehicles equipped with a TWC only.

5.2 SDBC

Thermal ageing is once again one of the most important deterioration mechanisms for catalytic after-treatment systems used in diesel vehicles such as oxidation catalysts and SCR systems. On the other hand, chemical poisoning and ash contamination may play a more important role in diesel vehicles than in gasoline ones, due to:

- The presence of the DPF;

- Lower exhaust temperatures;
- Usually higher mileage for vehicles of the same age (that means higher lubricant consumption);
- Completely different fuel/combustion processes (soot production in gasoline engines is usually low).

As an example, in the case of DPFs the deposition and accumulation of ash coming from lubricant and fuel is a very important deterioration mechanism. Ash accumulation in the filter channels, which strongly depends on lube oil consumption [48]-[53], affects the evolution of filter backpressure [54] and the flow of the exhaust gas.

The accelerated ageing procedure proposed for diesel vehicles in the implementing Regulation 692/2008 [3] and consequently in the current UN/ECE Regulation No.83 [42], is based on the use of the SDBC and focuses only on the number of regeneration/desulphation cycles. To a certain extent this is correct since regeneration/desulphation events are critical for the deterioration process of DPFs and NOx-storage catalysts because of the very high temperatures reached.

However, the current version of the SDBC does not take into account the thermal load on the after-treatment devices between two regeneration events during normal operating conditions. This may be a problem, for example, for filters that are passively regenerated (mainly relevant for HD engines).

In addition, while the SDBC can be appropriate to address the thermal ageing of after-treatment device technologies typical of Euro 5 diesel vehicles (for which it was designed), it does not cover satisfactorily other sources of efficiency deterioration (e.g. ash deposition and chemical poisoning). Therefore, it is not clear to what extent future after-treatment technologies introduced to comply with Euro 6 emission standards are covered by the current procedure.

Summarizing, the following potential issues can be identified as far as the application of the SDBC is concerned:

- The procedure focuses on the thermal load generated during the regeneration of particle filters but does not take into account the thermal load to the after-treatment devices during normal operating conditions. Nevertheless, this may be a minor problem if the tendency to increase the frequency of active regeneration, as discussed previously in Chapter 3, is confirmed. In other words, due to the typically low exhaust temperature of diesel vehicles and the high frequency of active regeneration, the SDBC could be already appropriate to cover the vast majority of the thermal ageing process of the devices used in Euro 6 cars;

- The SDBC does not cover adequately other deterioration mechanisms like chemical poisoning and ash deposit formation that are expected to play a more important role for DPFs (especially if a FBC is used to promote regeneration) than for three-way catalysts in PI vehicles;

- The procedure does not account for mechanical deterioration (e.g. due to vibrations, impacts…), which however is not currently considered in any legislative accelerated ageing procedure;

- The SDBC definition given by the legislation is vague and does not clarify how the load/speed conditions recorded over the SRC should be reproduced in the accelerated aging procedure.

Possible modifications

Alternative accelerated aging procedures for diesel vehicles are discussed in the following paragraphs in order to identify possible solutions to overcome the limitations of the SDBC procedure mentioned above.

During the DAAAC Symposium in 2008 [55] the Southwest Research Institute (SwRI) proposed a project for the development of a Diesel After-treatment Accelerated Ageing Cycle (DAAAC). The objective of the DAAAC project was to develop a protocol to generate accelerated ageing cycles capable of reproducing the typical in-use deterioration mechanisms of after-treatment devices used for HD diesel engines in a shorter time compared to real-world ageing process. More specifically, the target was to reduce the artificial ageing time to a maximum of 10% of the actual real-world ageing time. Several OEMs joined the project that has been recently completed with a validation phase in which artificially aged systems were compared to field-aged identical systems. Although the protocol was developed specifically for HDVs, there is no theoretical reason why the same methodology could not be extended to LDVs.

The DAAAC-HD protocol addresses the following deterioration mechanisms:

- Thermal ageing
- Chemical poisoning
- Deposit formation

The protocol consists of the following steps[4]:

1. Data collection phase. Time-at-temperature data for the selected after-treatment devices are collected during normal operating conditions. The data collection should last for the time needed to obtain a representative picture of the thermal load on the devices. Oil consumption, regeneration frequency, engine speed and load have to be also recorded.
2. Data processing. The time-at-temperature data of each considered after-treatment device is processed and converted to a single temperature ageing time by means of the Arrhenius equation. In this way, the in-use thermal load on the after-treatment device extrapolated over its useful life is converted in an equivalent thermal load to be obtained by exposing the device to a single arbitrary temperature for a given time. This step is substantially identical to the procedure described in the UN-ECE Reg. 83 for gasoline engines [42].
3. On the basis of the recorded real-world load/speed distribution, a representative stationary ageing cycle consisting of a given number of steady state conditions is generated by means of the K-cluster algorithm. The purpose of this ageing cycle is to replicate satisfactorily the range of exhaust flow rate and temperature variations observed in the real-world conditions. Exposing the after-treatment device at a single constant temperature and exhaust flow rate would not simulate adequately the real-world ageing process.
4. As a consequence, the ageing cycle will result in a continuously varying exhaust flow rate that simulates real-world operating condition dynamic. The exhaust temperatures to which the after-treatment devices are exposed during the ageing cycle can be optimized (for example by changing the engine settings, insulating the exhaust pipe, moving the devices closer to the exhaust manifold) in order to reduce the time needed to reproduce the equivalent thermal load calculated in step 2.
5. The lubricant consumption rate measured in real-world operating conditions is used to calculate how much lubricant would be consumed over the useful life of a specific after-treatment system. This represents the total oil consumption target to be reproduced in the accelerated ageing procedure. An additional oil consumption mode, selected among the operating conditions with the highest oil consumption, can be added to the ageing cycle in order to achieve the total oil consumption target. In order to speed up the process, the oil consumption can be artificially increased by flipping the piston rings of the engine used to generate the exhaust gas.
6. Finally, in case of a filter with active regeneration, a regeneration mode is also added.

The ageing cycle built in this way is repeated until the total thermal load and the total oil consumption targets are both reached. In the DAAAC project, the correlation between such accelerated ageing procedure and the real world has been demonstrated (at least to a certain extent) by comparing identical systems artificially aged with "naturally" aged system taken from the field with satisfactory results. In particular, the results achieved by flipping the piston rings to increase oil consumption compared very well with observations from field-aged systems; therefore modifications to the SDBC accelerated aging procedure for diesel vehicles could be inspired to the DAAAC protocol.

As far as the ash deposition is concerned, a different approach was studied by University of Tennessee and Oak Ridge National Laboratory. An accelerated ash loading procedure for DPFs has been developed since

---

[4] The Protocol is described in a confidential document distributed to clients of DAAAC-HD and SwRI.

2006 [56][57]. The developed protocol consists in increasing lube oil consumption by means of lube oil fuel doping, resulting in a large increase of ash accumulation rate. Fuel doping at 5% by volume was estimated to increase oil consumption by ~40 times with respect to the normal engine behaviour. As a result, a 60-hours experiment can simulate approximately 145,000 km of real-world driving [57]. The protocol also includes soot loading, active regeneration and periodic shutdown for filter weighing. The composition and distribution of the ash along the length of the DPFs within the channels were determined using EPMA (Electron Probe Microanalysis) and SEM-EDS (Scanning Electron Microscopy with Energy Dispersive X-Ray Spectroscopy). The ash loading of DPFs was found to be consistent with results from literature, with the ash layer thickness and total quantity of ash loaded increasing along the length of the DPF.

Additional experiments on fuel doping with lube oil for accelerated ash loading of DPFs revealed an ash plug-type distribution similar to what is usually observed after real-world on-road driving [58]. The developed test protocol included controlled dosing of lube oil into the fuel, engine conditions that enabled the formation of soot cake within the inlet channels, and periodic active regenerations to combust the soot.

However, within the DAAAC project, fuel doping was discarded at an early stage by all the consortium members on the basis of literature data and in-house experience, and was not further investigated.

As a matter of fact, doping fuel with lubricant is considered to not properly reproduce the effect of natural oil consumption for a number of reasons [59]:

1. Fuel doping accelerates only one of the two primary oil consumption pathways, namely the liquid losses that normally occur when oil passes around the top ring; when compared to evaporative oil consumption, this mechanism only accounts for 60% of total oil consumption;
2. Oil doping changes the ash/soot relative proportion in the exhaust, thus affecting any reactions that may take place between the two;
3. Oil doped into diesel fuel gets burned in the diffusion part of the flame front, while normally it would happen in the air rich regions;
4. Oil doping may disturb the micelles within the lubricant, potentially forming a fully or partially suspended sludge of metallic components, which may not burn as usual.

5.3 REVIEW OF DETERIORATION FACTORS: EXISTING DATA FOR EURO 6-LIKE VEHICLES CERTIFIED IN THE USA

According to current European emissions legislation for light-duty vehicles [3], each manufacturer can choose whether to:

(i) Physically test the durability of after-treatment systems or

(ii) Follow the alternative approach of using assigned DFs (**Table 5**).

In the first case, the manufacturer can opt for full mileage accumulation test (160,000 km) with the candidate vehicle or to use an accelerated bench ageing durability test according to the standard procedures defined in the regulation.

Table 5: Assigned Multiplicative DFs for Euro 5/6 vehicles [3]

Engine Category	Assigned Deterioration Factors (160.000 km)						
	CO	THC	NMHC	NOx	HC+NOx	PM	PN
Positive-ignition	1.5	1.3	1.3	1.6	-	1.0	1.0
Compression-ignition (Euro 5)	1.5	-	-	1.1	1.1	1.0	1.0
Compression-ignition (Euro 6) *							

* Euro 6 Deterioration Factors to be determined

In Europe, the use of the assigned deterioration factors is by far the most preferred option by the car manufacturers. The reasons of that are quite obvious: lower costs and reduced time for the type approval of vehicles. Indeed, being the (multiplicative) DF defined as the ratio between mass emission of the considered pollutant at 160,000 km and at 6,400 km, it is sufficient for the car manufacturer to prove that the initial emission value multiplied by the assigned DF still satisfies the relevant emission standard requirement. In other words, the use of the assigned deterioration factors implies that the emission limits have to be met with an adequate safety margin, given by the DF, which accounts for the deterioration of the conversion efficiency over the useful life of the after-treatment device.

However, from a theoretical point of view, the use of the deterioration factors does not guarantee the compliance with the durability requirements, as shown in **Figure 6**. In fact, a system with a high initial conversion efficiency (case A in the Figure) could result, at the end of its useful life, either in emission levels lower than the relevant limit (dashed blue line) or exceeding the limit (dash-dotted blue line) depending on the actual deterioration rate. On the other hand, a system with a lower initial conversion efficiency (case B in the Figure, dotted green line) might have much better performance at the end of its useful life if the deterioration rate is lower than the assigned DF. Hence, the margin between the actual emissions level at type approval and the limit may not be indicative of the emissions performance over the entire useful vehicle life.

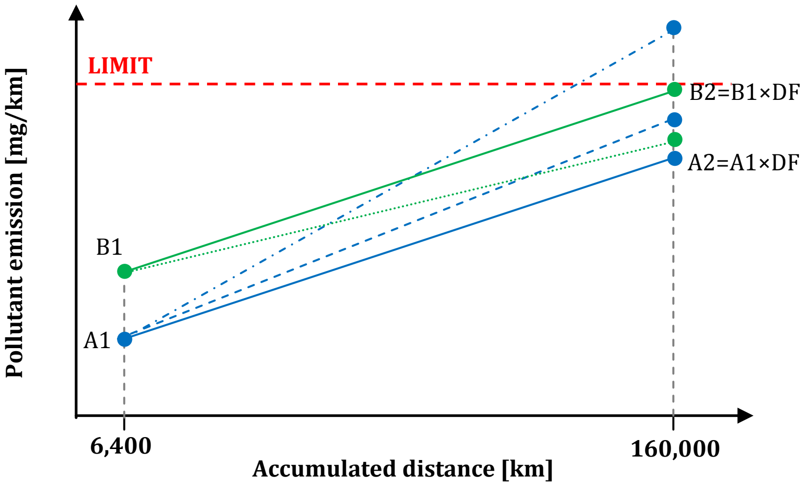


Figure 7: Application of assigned DF.

The conversion efficiency can be related to the precious metals load of the catalyst and due to the cost of these metals, the tendency is to minimize their load on the catalyst. Therefore, from the point of view of production cost, a durable catalyst with a low metal content should be economically more viable for OEMs than a highly efficient catalyst with a higher deterioration rate. This is of course valid only for systems using precious metals. In any case, as shown above, the fact that the limit is met with an adequate margin does not provide any information on the actual deterioration rate.

Although current European legislation on durability demonstration was inspired by the relevant US provisions, there are major differences between the US and the European approach as far as durability is concerned. According to US EPA Durability Compliance Program [59], durability demonstration can be achieved in a variety of different ways. These include standard whole-vehicle testing, bench ageing procedures to calculate DFs or even installing aged components on the emission data vehicle (EDV) prior to emission testing. Car manufactures may use accelerated deterioration methods and artificial ageing techniques to simulate wear on vehicle and emission system components, in order to predict in-use emission levels and deterioration rates for vehicles they wish to certify. Manufacturers may also use proprietary ageing cycles to conduct their durability program, but then they must develop an equivalency factor with the standard EPA ageing cycle (SRC). All manufacturer durability program plans must be annually submitted to EPA for review and approval; a list of manufacturer equivalency factors and other applicable vehicle information for each model year is provided on the EPA website [61]. In the case of small volume manufacturers and small volume test groups, there is instead the possibility to use EPA assigned DFs [60], listed in **Table 6**[5].

Table 6: Tier 2 Gasoline Exhaust Emission Assigned Additive DFs [60]

Engine Category	Assigned Additive Deterioration Factors [g/mi] (120.000 mi)[i, iv]						
	NMOG	CO	NOx	HCHO	PM	THC	NMHC
Tier 2 –Bin 5	0.012	0.3	0.01	0.3	-[ii]	0.013[iii]	0.011[iii]

[i] Assigned DFs are also applicable to gasoline hybrid, ethanol FFVs, CNG, LNG and LPG vehicles.
[ii] Not enough PM data available; compliance statements may be used in lieu of PM measurement.
[iii] Values not provided by EPA but calculated following EPA defined Conversion Factors for Hydrocarbon Emission Components [62].
[iv] Table 6 is not applicable to diesels.

The main difference between the US and the EU legislation concerns the in-use compliance strategy. As seen above, while car manufacturers in US can quite freely define in-house procedures to demonstrate durability of vehicles and engines, actually EPA strongly relies on the information gathered from in-use emission testing programmes. This data is used to periodically review the effectiveness of the adopted procedures in covering the significant majority (meaning approximately 90%) of the distribution of emission levels and deterioration grades experienced over the full and intermediate useful life of candidate in-use vehicles [59]. EPA may also request an analysis to evaluate a durability procedure and withdraw its approval or demand modifications in case the durability objective is not met as a result of the comparison between the declared DFs and the in-use emission data. The European approach gives instead much more importance to the type approval procedure. Another difference concerns assigned deterioration factors (ADFs) that in the USA can be used only by small volume manufacturers and small volume test groups while in Europe all manufacturers can currently opt for the use of ADFs.

If there is no change in the current EU approach on durability demonstration, it is clear that the assigned DFs for Euro 6 have to be carefully defined in order to cover the typical deterioration rates. Unfortunately, data for Euro 6 vehicles are not yet publicly available in EU; on the contrary, US legislation [59] prescribes publication of vehicle certification data on EPA website [61], including DFs. Among those data, DFs declared by car manufacturers for gasoline and diesel cars that can be considered equivalent to Euro 6 vehicles from technology point of view, were processed and compared with the Euro 5 deterioration factors defined in the European legislation (see **Tables 7-10** and **Tables A1-A4** in the Appendix).

Deterioration factors declared by car manufacturers and those assigned by EPA are only of the additive type (see Section 4.3) while in the past multiplicative DFs were set. With regard to the use of additive or multiplicative deterioration factors, this is well explained in a document presented during the Euro 5 comitology process by the Japanese Automobile Manufacturers Association (JAMA) [63]. In this document it is shown that multiplicative DF may lead to aberrant emission values, due to the fact that the slope of the interpolated line can be strongly influenced by the variability of the measured emissions especially when the values are very low. The example provided in the document considers three different vehicles (see **Figure 7** and **Figure 8**). As a result of the calculation based on the interpolation of the measured emission levels, the multiplicative DF of Vehicle B becomes much higher than that of Vehicle A, although its emissions are lower, and consequently an estimated value at 80,000 km of Vehicle A becomes lower than that of Vehicle B. In the case of vehicle C, the deterioration becomes even negative as well as the interpolated emission value at 6400 km. This is the reason why additive DF are sometime preferred to multiplicative DFs.

---

[5] EPA Assigned DFs have been determined as the 70th percentile values among the additive DFs declared by car manufacturers, according to provisions for small volume manufacturers and small volume test groups [59].

Table 7: Comparison between *ADD DF* and *MULT DF* [63].

Travel distance (10 thousand km)	Example of Exhaust Gas Value		
	Vehicle A	Vehicle B	Vehicle C
0.3	3.0	2.0	0.5
0.5	3.0	2.0	0.5
2	4.5	2.0	0.5
4	4.5	3.0	1.5
6	5.5	5.0	2.0
8	**6.5**	**6.0**	**5.5**
***MULT DF* (yE/y0)**	1.999	4.280	-13.101
Estimated value at 80K km (value at 3K km × *MULT DF*)	**5.997**	**8.561**	**-6.550**
***ADD DF* (yE-y0)**	3.212	4.509	4.732
Estimated value at 80K km (value at 3K km + *ADD DF*)	**6.212**	**6.509**	**5.232**

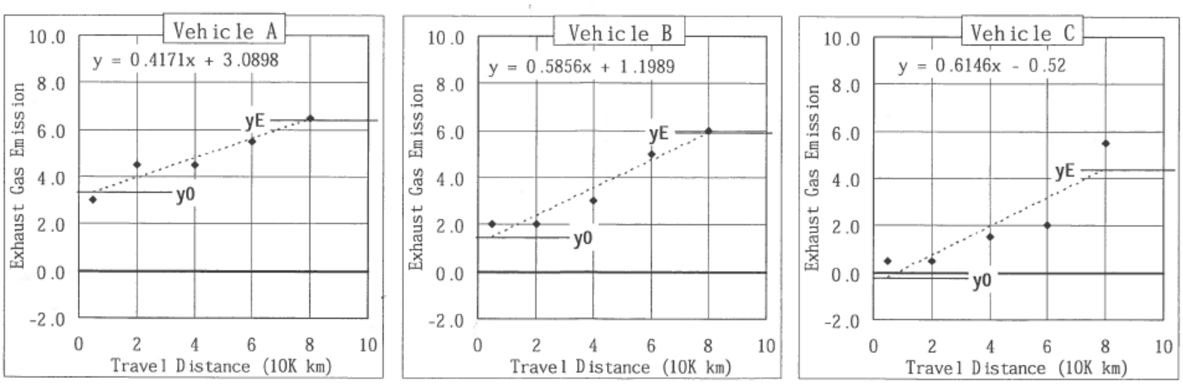


Figure 8: Explanatory examples for additive vs. multiplicative DFs [63].

For a comparison with the assigned Euro 5 DFs, which are given in the multiplicative form, multiplicative factors (*MULT DF*) were calculated from the additive values (*ADD DF*) according to the formula [63] as defined in Section 4.3 above:

$$ADD\ DF = LIMIT - \frac{LIMIT}{MULT\ DF}$$

Where corresponding values for LIMIT were set according to EPA emission limits [59]. Since no limit is set by EPA for THC and NMHC emissions, corresponding additive deterioration factors where derived by using EPA conversion factors for hydrocarbon emission components [62].

DFs were available for 18 diesel LDVs (15 different vehicle models) and LDTs[6] (model years 2011-2014). The number of diesel vehicles certified is much lower than the number of certified gasoline vehicles, reflecting the typical situation of the US car market. The complete list of vehicles included in the analysis is available in Appendix 1 (**Table A 1**); further information about implemented after-treatment devices and declared additive DFs is also provided. Multiplicative DFs at 160,000 km (100,000 mi) were derived from additive DFs at 190,000 km (120,000 mi) declared by car manufacturers (see **Table A 2**).
For each vehicle considered, information concerning the implemented after-treatment systems was retrieved from EPA's Transportation and Air Quality Document Index System (DIS) [64].

---

[6] EPA categories for Light-Duty Trucks correspond respectively to European LDT N1 CL3 (for LDT2) and LDT NC1 CL2 (for LDT1, LDT3, LDT4).

Four different combinations of after-treatment devices were adopted[7] in the studied vehicles:

1. DOC+DPF+SCR (12 vehicles)
2. DOC+DPF+SCR+ LNT (2 vehicles)
3. DOC+DPF+ LNT (2 vehicles)
4. DOC+DPF+SCR+SCR (2 vehicles)

The exact layout of the exhaust system and in particular the order in which the devices are positioned on the exhaust pipe was not described in detail in the available documentation.

The most common after-treatment system was found to be type 1: DOC+DPF+SCR. Among the considered diesel LDVs, higher CO and NMHC DFs were observed for the two vehicles implementing the second option; three over four vehicles with a LNT system on-board (option 2 and 3) presented a higher DF also for NOx emissions. Further details are available in Appendix 1 (**Figure A 6** to **Figure A 10**).

Table 8 and **Table 9** below summarize results for average values and 90th percentile of DFs for all regulated pollutants plus methane, calculated at 190,000 km and 160,000 km respectively. The 90th percentile was chosen as reference value since it is considered to be representative of the "vast majority" of analysed vehicles (according to EPA 40 CFR Part 86 [42]), while the average value would cover only half of the vehicle population.

Table 8: Calculated Multiplicative DFs for diesel vehicles (MY 2011-14) at 190,000 km

	Calculated Multiplicative DFs (190,000 km /120,000 mi)					
	CO	THC	NMHC	NOx	PM	CH_4
AVERAGE VALUE	1.215	1.165	1.214	1.114	1.023	1.173
90th PERCENTILE	1.498	1.221	1.276	1.315	1.086	1.409

Table 9: Calculated Multiplicative DFs for diesel vehicles (MY 2011-14) at 160,000 km

	Calculated Multiplicative DFs (160,000 km /100,000 mi)					
	CO	THC	NMHC	NOx	PM	CH_4
AVERAGE VALUE	1.147	1.133	1.157	1.089	1.019	1.136
90th PERCENTILE	1.359	1.178	1.220	1.248	1.071	1.319
ASSIGNED Euro 5	*1.5*			*1.1*	*1.0*	

The results show that assigned Euro 5 DFs are not far from the 90th percentile values derived from the declared DFs at 160,000 km. Euro 5 DFs are slightly higher in the case of CO and slightly lower for NOx and PM. However, significant differences were noticed when considering separately LDVs and LDTs, with significantly higher DF values for light-duty vehicles (see **Figure A 4** and **Figure A 5**).

A similar analysis was then performed for gasoline LDVs and LDTs model year (MY) 2014. Certification durability data for 131 vehicles (different vehicle models) from EPA database [61] were available and analysed (see **Table A 3** in Appendix 2). Multiplicative DFs at 160,000 km (100,000 mi) were then calculated from declared additive values at 190,000 km (120,000 mi). Calculated DFs for all regulated pollutants plus methane are recorded in **Table A 4**, and overall values are summarized in **Table 10** and **Table 11**.

---

[7] As declared in the manufacturer's Application for Emission Certification file available on EPA DIS.

Charts collecting graphical information about analysed data are available in Appendix 2, **Figure A 11** to **Figure A 16**. Results show that Assigned Euro 5 DFs overestimate the 90th percentile values at 160,000 km (Δ=11÷17%) except in the case of PM. This means that the vast majority of considered vehicles perform better compared to deterioration rates assumed by the Euro 5 regulation [3].

The comparison between assigned EPA values and multiplicative deterioration factors derived from manufacturers data showed that EPA assigned DFs are lower than 90th percentile values (differences in the range 2%-16%), according to what expected: the calculated DFs are based on the 90th percentile of the collected data, while the EPA assigned DFs have been estimated as the 70th percentile values of the OEM additive DFs. It was also found that LDTs generally show higher CO and lower NOx deterioration factors respect to LDVs.

A more detailed analysis of the dataset highlighted that vehicles with the lowest NOx DF (≈1) are mostly luxury/high level vehicle models while only few vehicles exceeded the assigned NOx DF value of 1.6.

Table 10: Calculated Multiplicative DFs for gasoline vehicles (MY 2014) at 190,000 km

	Calculated Multiplicative DFs (190,000 km /120,000 mi)					
	CO	**THC**	**NMHC**	**NOx**	**PM**	**CH_4**
AVERAGE VALUE	1.111	1.107	1.083	1.221	1.086	1.537
90th PERCENTILE	1.224	1.189	1.153	1.500	1.321	1.764
LDV 90th PERCENTILE	1.292	1.188	1.154	1.499	1.321	1.761
LDT 90th PERCENTILE	1.167	1.169	1.135	1.479	1.193	2.409
ASSIGNED EPA[i]	*1.1*	*1.1*	*1.1*	*1.2*		

[i] Multiplicative DFs calculated from EPA assigned additive DFs.

Table 11: Calculated Multiplicative DFs for gasoline vehicles (MY 2014) at 160,000 km

Statistical Variability Indexes	**Calculated Multiplicative DFs (160,000 km /100,000 mi)**					
	CO	**THC**	**NMHC**	**NOx**	**PM**	**CH_4**
AVERAGE VALUE	1.108	1.042	1.055	1.150	1.001	1.197
90th PERCENTILE	1.240	1.119	1.116	1.424	1.000	1.493
LDV 90th PERCENTILE	1.229	1.120	1.121	1.424	1.000	1.519
LDT 90th PERCENTILE	1.414	1.064	1.071	1.349	1.000	1.210
ASSIGNED Euro 5	*1.5*	*1.3*	*1.3*	*1.6*	*1.0*	
ASSIGNED EPA[i]	*1.1*	*1.1*	*1.1*	*1.2*		

[i] Multiplicative DFs calculated from EPA assigned additive DFs.

Summarizing the results (see **Table 12**), the analysis of the declared DFs showed that in the case of gasoline vehicles the Euro 5 assigned DFs for gaseous emissions are more conservative. The situation is quite different for PM, for which the real DFs seem to be higher than the Euro 5 assigned factor. As far as diesel vehicles are concerned, the 90th percentile of the declared DFs for NOx appears to be slightly higher than the Euro 5 assigned DF.

Table 12: Multiplicative DFs for Euro 6 vehicles

	Calculated Multiplicative DFs (160,000 km)					
	CO	THC	NMHC	NOx	PM	CH_4
ASSIGNED Euro 5 – PI	*1.5*	*1.3*	*1.3*	*1.6*	*1.0*	
Derived Euro 6 – PI 90th percentile	1.224	1.189	1.153	1.500	1.321	1.764
ASSIGNED Euro 5 - CI	*1.5*			*1.1*	*1.0*	
Derived Euro 6 – CI 90th percentile	1.359	1.178	1.220	1.248	1.071	1.319

6 CONCLUSIONS

The report deals with the approaches and the legislative procedures to control the durability of exhaust after-treatment systems in the European Union and the USA.

An overview of the main ageing mechanisms of after-treatment devices used to control exhaust emissions is initially provided. Thermal ageing results to be the major deactivation mechanism for all catalytic after-treatment devices, followed by ash plugging in the case of DOC, SCR and LNT. The most important degradation mechanism for DPF and GPF is instead represented by ash deposition; soot from incomplete regeneration can also contribute to DPF plugging.

Current legislative procedures for durability demonstration are then described and analysed; emphasis is placed on the differences between vehicles with positive and compressed ignition engines, and on the comparison with current US regulation on emission durability. In particular, the accelerated ageing procedure for PI vehicles, based on the Standard Bench Cycle (SBC), appears to be appropriate for reproducing thermal ageing, which is the dominant effect for three-way catalysts commonly applied to this vehicle category. Nevertheless, a more careful evaluation of the suitability of the SBC for Euro 6 gasoline vehicles equipped with GPF is recommended.

The Standard Diesel Bench Cycle (SDBC) defined for CI vehicles is examined as well, and it is concluded that it properly addresses the impact of the thermal stress on the after-treatment devices due to the high temperatures reached during the regeneration of the DPFs. However, the SDBC does not cover adequately other deterioration sources and the following main issues can be identified:

- The current procedure focuses on the thermal load generated during the regeneration of the DPF, which is important, but does not take into account the thermal load to the after-treatment devices during normal operating conditions. Nevertheless, this may be a minor problem if the tendency to increase the frequency of active regeneration is confirmed. In other words, due to the typically low exhaust temperature of diesel vehicles and the high frequency of active regeneration, the SDBC could be already appropriate to cover the vast majority of the thermal ageing of the devices used in Euro 6 cars;
- It does not cover adequately other deterioration mechanisms like chemical poisoning and deposit formation that are expected to play a relatively more important role compared to gasoline vehicles (especially if a FBC is used to promote regeneration);
- The procedure does not account for mechanical deterioration (e.g. due to vibrations, impacts…), which however is not currently considered in any legislative accelerated ageing procedure;
- The SDBC definition given by the legislation is very vague and does not clarify how the load/speed conditions recorded over the SRC should be reproduced in the accelerated aging procedure.

Different approaches currently under development by other research organizations are also considered. The protocol developed within the DAAAC protocol appears to be a good alternative solution and elements from this protocol could be taken and introduced in the European legislation.

Finally, a review of deterioration factors available in the US-EPA website for vehicles certified for the US market is presented, in order to evaluate the variability of performance degradation for latest after-treatment technologies. Multiplicative DFs based on the 90th percentile of values declared by car manufacturers are derived for the last generation of gasoline and diesel passenger cars that could be considered representative of current and future Euro 6 vehicles. Results show that assigned Euro 5 DFs are not far from the 90th percentile values. For diesel vehicles, Euro 5 DFs are slightly higher than 90th percentile in the case of CO and lower for NOx and PM, meaning that for most of the considered vehicles CO emissions deteriorate slower compared to what assumed by the Euro 5 Regulation, while emissions of the remaining regulated pollutants deteriorate faster. For gasoline vehicles instead, assigned Euro 5 DFs are significantly higher than 90th percentile values except in the case of PM, implying that the vast majority of considered vehicles perform considerably better compared to deterioration rates assumed by the Euro 5 regulation.

REFERENCES

[1] K. Lindqvist, Emission standards for light and heavy road vehicles, AirClim Factsheet no. 25, January 2012.

[2] J. Lents, M. Walsh, K. He, N. Davis, M. Osses, S. Tolvett, H. Liu, Handbook of Air Quality Management - Developing Emission Reduction Strategies, 2009.

[3] COMMISSION REGULATION (EC) No 692/2008 implementing and amending Regulation (EC) No 715/2007 of the European Parliament and of the Council on type-approval of motor vehicles with respect to emissions from light passenger and commercial vehicles (Euro 5 and Euro 6) and on access to vehicle repair and maintenance information, 2008.

[4] COMMISSION REGULATION (EU) No 582/2011 of 25 May 2011 implementing and amending Regulation (EC) No 595/2009 of the European Parliament and of the Council with respect to emissions from heavy-duty vehicles (Euro VI) and amending Annexes I and III to Directive 2007/46/EC of the European Parliament and of the Council, 2011.

[5] D. Ignatov, C. Küpper, S. Pischinger, M. Bahn, W. Betton, O. Rütten, R. Weinowski, Catalyst Ageing Method for Future Emissions Standard Requirements, SAE International, 2010.

[6] P. Eastwood, Critical Topics in Exhaust Gas After-treatment, Research Studies Ltd, 2000.

[7] F.M.Z. Zotin, O. Da Fonseca Martins Gomes, C.H. De Oliveira, A.A. Neto, M.J.B. Cardoso, Automotive catalyst deactivation: Case studies, Catalysis Today Vol. 107-108, pp. 157-167, 2005.

[8] J. Kašpar, P. Fornasiero, N. Hickey, Automotive catalytic converters: current status and some perspectives, Catalysis Today Vol. 77, pp. 419–449, 2003.

[9] N. Guillen-Hurtado, V. Rico-Perez, A. Garcia-Garcia, D. Lozano-Castello, A. Buen-Lopez, Three-Way Catalyss: Past, Present and Future, Dyna, Vol. 79 (75), pp. 114-121, 2012.

[10] T. V. Johnson, Vehicular Emissions in Review, SAE International, 2012.

[11] SAE 2012 World Congress, Vehicular emissions control highlights of the annual Society of Automotive Engineers (SAE) international congress, Reviewed by Timothy V. Johnson, Platinum Metals Rev., Vol. 57 (2), pp. 117–122, 2013.

[12] J. Li, T. Szailer, A. Watts, N. Currier, et al., Investigation of the Impact of Real-World Ageing on Diesel Oxidation Catalysts, SAE Int. J. Engines, Vol. 5(3), pp. 985-994, 2012.

[13] S. Eaton, B. Bunting, T. Toops, K. Nguyen, The Roles of Phosphorus and Soot on the Deactivation of Diesel Oxidation Catalysts, SAE Technical Paper, 2009.

[14] M. H. Wiebenga, C. Hwan Kim, S. J. Schmieg, S. H. Oh et al., Deactivation mechanisms of Pt/Pd-based diesel oxidation catalysts, Catalysis Today, Vol. 184, pp. 197– 204, 2012.

[15] W. Addy Majewski, Selective Catalytic Reduction, www.DieselNet.com. Copyright © Ecopoint Inc. Revision 2005.05l, 2005.

[16] I. Malpartida, O. Mariea, P. Bazina, M. Daturia, X. Jeandelb, An operando IR study of the unburnt HC effect on the activity of a commercial automotive catalyst for NH3-SCR, Applied Catalysis B: Environmental, Vol. 102, pp. 190–200, 2011.

[17] A. Williams, J. Burton, R.L. McCormick, T. Toops et al., Impact of Fuel Metal Impurities on the Durability of a Light-Duty Diesel After-treatment System, SAE International, 2013.

[18] Bret Zimmerman, SCR in a Small Car World - Combined SCR Technology, Proceedings of the 6th International Conference on Selective Catalytic Reduction, 2013.

[19] W.E.J. van Kooten, H.C. Krijnsen, C.M. van den Bleek, H.P.A. Calis, Deactivation of zeolite catalysts used for NOx removal, Applied Catalysis B: Environmental, Vol. 25, pp. 125–135, 2000.

[20] G. Liu and P.-X. Gao, A review of NOx storage/reduction catalysts: mechanism, materials and degradation studies, Catal. Sci. Technol., Vol. 1, pp. 552–568, 2011.

[21] D. Chan, A. Gremminger, O. Deutschmann, Effect of Hydrothermal Ageing on Physical and Chemical Properties of a Commercial NOx-Storage Catalyst, Top Catal Vol. 56, pp. 293–297, 2013.

[22] S. Benramdhane, C.-N. Millet, E. Jeudy, J. Lavy, V. Blasin Aubéb, M. Daturi, Impact of thermal and vehicle ageing on the structure and functionalities of a lean NOx-trap, Catalysis Today, Vol. 176, pp. 56– 62, 2011.

[23] D. Adouane, H. Dutilleul, P. Guibert, M. Teixeira, et al., Impact of Thermal and Engine Ageing on a Fully Formulated Lean NO_x Trap, SAE Technical Paper 2012-01-1746, 2012.

[24] C. Favre, J. May, D. Bosteels, Emissions Control Technologies to Meet Current and Future European Vehicle Emissions Legislation, Association for Emission Control by Catalyst (AECC), www.aecc.eu.

[25] A. G. Konstandopoulos, E. Papaioannou, Update on The Science and Technology of Diesel Particulate Filters, KONA Powder and Particle Journal, No.26, 2008.

[26] D. Zarvalis, S. Lorentzou, A. G. Konstandopoulos, Fast Evaluation Method of the Ash Ageing Effect on Catalyzed Diesel Particulate Filters, European Aerosol Conference, Karlsruhe, 2009.

[27] R. Zhan, DPF Durability, Southwest Research Institute Symposium, 2008.

[28] P. Charbonneau, A Study of Soot Cake Formation in a Diesel Particulate Filter, Master of Applied Science, Department of Mechanical and Industrial Engineering, University of Toronto, 2009.

[29] A. Mamakos, Feasibility of Introducing Particulate Filters on Gasoline Direct Injection Vehicles, JRC Report EUR 25297 EN, 2011.

[30] I. Mikulic, H. Koelma, S. Majkowski, P. Vosejpka, A study about particle filter application on a state-of-the-art homogeneous turbocharged 2L DI gasoline engine. Proceeding of 19th Aachen colloquium, pp. 449–66, 2010.

[31] R. Zhan, S.T. Eakle, P. Weber, Simultaneous Reduction of PM, HC, CO and NOx Emissions from a GDI Engine, SAE Technical Paper 2010-01-0365, 2010.

[32] J. Andersson, M. Keenan, K. Åkerman, GDI Particles – Legislation, Current Levels and Control, Cambridge Particle Meeting, 2009.

[33] C. Saito, T. Nakatani, Y. Miyairi, K. Yuuki et al., New Particulate Filter Concept to Reduce Particle Number Emissions. SAE Technical Paper 2011-01-0814.

[34] A. Mamakos, C. Dardiotis, G. Martini, Assessment of particle number limits for petrol vehicles, JRC Report EUR 25592 EN, 2012.

[35] A. Mayer, A. Ulrich, J. Czerwinski and J. Mooney, Metal-Oxide Particles in Combustion Engine Exhaust. SAE Technical Paper 2010-01-0792, 2010.

[36] T. Chan, E. Meloche, J. Kubsh, D. Rosenblatt et al., Evaluation of a Gasoline Particulate Filter to Reduce Particle Emissions from a Gasoline Direct Injection Vehicle, SAE Int. J. Fuels Lubr. Vol. 5, No.3, pp. 1277-1290, 2012.

[37] J. Richter, R. Klingmann, S. Spiess, K. Wong, Application of Catalyzed Gasoline Particulate Filters to GDI Vehicles, SAE Int. J. Engines Vol. 5(3), pp. 1361-1370, 2012.

[38] T. Shimoda, Y. Ito, C. Saito, T. Nakatani et al., Potential of a Low Pressure Drop Filter Concept for Direct Injection Gasoline Engines to Reduce Particulate Number Emission, SAE Technical Paper 2012-01-1241, 2012.

[39] S. Zinola, M. Leblanc, B. R'Mili, A. Boréave et al., Particle number characterization from a spark ignition direct injection engine with a gasoline particulate filter, Proceedings of the 17th ETH-Conference on Combustion Generated Nanoparticles, 2013.

[40] P. Kattouah, K. Kato, D. Thier, E. Ohara et al., Latest Particulate Filter Technology to Reduce Particle Emissions from Gasoline Engines, Proceedings of the 17th ETH-Conference on Combustion Generated Nanoparticles, 2013.

[41] T. Boger, N. Gunasekaran, R. Bhargava, C. Bischof, Particulate Filters for DI Gasoline Engines, MTZ worldwide Edition, Vol. 74, 2013.

[42] United Nations Economic Commission for Europe, Addendum 82: Regulation No. 83 – Uniform provisions concerning the approval of vehicles with regard to the emission of pollutants according to engine fuel requirements, E/ECE/324/Rev.1/Add.82/Rev.4, 2011.

[43] J. Andersson, Issues Potentially Impacting the Measurement of PN during Regeneration of GPF and DPFs on Light-duty Vehicles, A discussion document for the PMP Working Group, March 2014.

[44] J. Song, J. Wang, A.L. Boehman, The role of fuel-borne catalyst in diesel particulate oxidation behaviour, Combustion and Flame, Vol. 146 (1–2), pp. 73-84, 2006.

[45] T. Seguelong, Fuel Borne Catalysts for Diesel Particulate Filter Regeneration, Proceedings of the Asian Vehicle Emission Control Conference (AVECC2001), Thailand, 2011.

[46] DieselNet Technology Guide, Diesel Filter Systems, www.DieselNet.com. Copyright © Ecopoint Inc. Revision 2005.06c.

[47] W. Givens, W. Buck, A. Jackson, A. Kaldor, et al., Lube formulation effects on transfer of elements to exhaust after-treatment system components, SAE Technical Paper 2003-01-3109, 2003.

[48] S. Nemoto, S. Togawa, Y. Kishi, T. Ishikawa, et al., Impact of oil-derived ash on continuous regeneration-type diesel particulate filter – JCAPII oil WG report, SAE Technical Paper 2004-01-1887, 2004.

[49] K. Kimura, M. Lynskey, E.R. Corrigan, D.L. Hickman, et al., Real World Study of Diesel Particulate Filter Ash Accumulation in Heavy- Duty Diesel Trucks, SAE Technical Paper 2006-01-3257, 2006.

[50] Y. Takeuchi, S. Hirano, M. Kanauchi, H. Ohkubo, et al., The Impact of Diesel engine Lubricants on Deposit Formation in Diesel Particulate Filters, SAE Technical Paper 2003-01-1870, 2003.

[51] R. Allansson, C. Goersmann, M. Lavenius, P.R. Phillips, et al., The Development and In-Field Performance of Highly Durable Particulate Control Systems, SAE Technical Paper 2004-01-0072, 2004.

[52] N. Jeuland, J.B. Dementhon, L. Gagnepain, G. Plassat, et al., Performances an Durability of DPF (Diesel Particulate Filter) Tested on a Fleet of Peugeot 607 Taxis: Final Results, SAE Technical Paper 2004-01-0073, 2004.

[53] E. Bardasz, S. Cowling, A. Panesar, J. Durham, et al., Effects of Lubricant Derived Chemistries on Performance of the Catalyzed Diesel Particulate Filters, SAE Technical Paper 2005-01-2168, 2005.

[54] P. Tandon, A. Heibel, J. Whitmore, N. Kekre, K. Chithapragada, Measurement and prediction of filtration efficiency evolution of soot loaded diesel particulate filters, Chemical Engineering Science Vol. 65, pp. 4751–4760, 2010.

[55] Southwest Research Institute, Diesel After-treatment Accelerated Ageing Cycles (DAAAC) website, http://www.swri.org/9what/events/confer/DAAAC/default.htm.

[56] B. Bunting, T. Toops, , K. Nguyen, S. Eaton, H. Kim, A. Youngquist, The development of rapid ageing and poisoning protocols for diesel after-treatment devices, Proceedings of DEER Conference, 2006.

[57] A. Youngquist, K. Nguyen, B. Bunting, T. Toops, Development of an Accelerated Ash Loading Protocol for Diesel Particulate Filters, SAE Technical Paper 2008-01-2496, 2008.

[58] T. Harris, A. Kozlov, P. Ayyappan, J. Combs, Engine Test Protocol for Accelerated Ash Loading of a Diesel Particulate Filter, SAE Technical Paper 2011-01-0607, 2011.

[59] EPA, 40 CFR Part 86, Emission Durability Procedures for New Light-Duty Vehicles, Light-Duty Trucks and Heavy-Duty Vehicles - Final Rule, Federal Register Vol. 71, No. 10, 2005.

[60] EPA Guidance letter to Manufacturers CD-12-07 (LDV/LDT/MDPV/HDV/ICI/LD-AFC), Assigned Deterioration Factors, March 20, 2012.

[61] EPA website, Cars and Light Trucks, Annual Certification Test Results & Data, http://www.epa.gov/otaq/crttst.htm.

[62] EPA, Conversion Factors for Hydrocarbon |Emission Components, EPA-420-R-10-015 NR-002d, 2010.

[63] Japan Automobile Manufacturers Association, JAMA's Comments on Comitology Part of Euro 5 Emission Regulation for European Light Duty Vehicles, October, 2006.

[64] EPA's Transportation and Air Quality Document Index System (DIS), http://iaspub.epa.gov/otaqpub/publist1.jsp.

APPENDICES

APPENDIX 1 - DFS FOR EURO 6-LIKE DIESEL VEHICLES

Table A 1: Certification durability data for Light-Duty diesel vehicles MY 2011-2014: declared additive DFs at 120,000 mi (190,000 km).

MY	***Manufacturer***	***Vehicle Model***	***Vehicle Class***	***After-treatment Devices*[8]**	***DECLARED ADDITIVE DFs [g/mi]*[9] *(190,000 km)***						
					NMOG	**CO**	**NOx**	**PM**	**CH4**	**NMHC[10]**	**THC[11]**
2012	AUDI	Q7	LDT3/ LDT4	1) DOC (Pt+Pd, Ceramic, Monolith) 2) DPF (Pt+Pd, Ceramic, Monolith) 3) SCR (Cu, Ceramic, Monolith)	0.017	0.118	0.011	0	0.017	0.017	0.0340
2014	AUDI	A8	LDV	1) DPF (Pt+Pd, Ceramic, Monolith) 2) DOC (Pt+Pd, Ceramic, Monolith) 3) SCR (Cu, Ceramic, Monolith)	0.0059	0.059	0.004	0.0007	0.0032	0.0059	0.0091
2014	AUDI	Q7	LDT3	1) DOC (Pt+Pd, Ceramic, Monolith) 2) DPF (Pt+Pd, Ceramic, Monolith) 3) SCR (Cu, Ceramic, Monolith)	0.012	0.209	0.004	0	0.012	0.012	0.0240
2014	AUDI	Q7	LDT4	1) DOC (Pt+Pd, Ceramic, Monolith) 2) DPF (Pt+Pd, Ceramic, Monolith) 3) SCR (Cu, Ceramic, Monolith)	0.012	0.209	0.004	0	0.012	0.012	0.0240
2013	BMW	X5 xDrive35d	LDT4	1) DOC (Pt+Pd, Ceramic, Monolith) 2) DPF (Pt+Pd, Metal, Monolith) 3) SCR (no precious metal, Metal, Monolith)		0.65	0.007	0		0.0186	
2014	BMW	328d xDrive Sports Wagon	LDV	1) DOC (Pt+Pd, Ceramic, Monolith) 2) DPF (Pt+Pd, Metal, Monolith) 3) SCR (no precious metal, Metal, Monolith) 4) Nox Adsorber (Pt+Pd+Rh, Ceramic, Monolith)		2.32	0	0		0.0568	
2014	BMW	535d xDrive	LDV	1) DOC (Pt+Pd, Ceramic, Monolith) 2) DPF (Pt+Pd, Metal Monolith) 3) SCR (no precious metal, Metal Monolith) 4) NOx Adsorber (Pt+Pd+Rh, Ceramic, Monolith)		2.75	0.023	0.0003		0.0208	
2011	Mahindra	TR40	LDT4	1) DOC 2) DPF 3) SCR	0.011	0.042	0	0			
2013	Mercedes-Benz	E 350 BLUETEC	LDV	1) DOC (Pt+Pd, Ceramic, Monolith) 2) DPF (Pt+Pd, Ceramic, Monolith)	0.0055	0.07	0	0.00008		0.0055	

---

[8] After-treatment devices: Type (Precious metal, substrate material, substrate construction).

[9] EPA website, Cars and Light Trucks, Annual Certification Test Results & Data [61].

[10] When not available, calculated based on the NMOG/NMHC ratio declared by the car manufacturer.

[11] Calculated as NMHC+METHANE values [62].

				3) SCR (no precious metal/ferric oxide, Ceramic, Monolith)							
2013	Mercedes-Benz	GL 350 BLUETEC	LDT4	1) DOC (Pt, Ceramic, Monolith) 2) DPF (Pt+Pd, Ceramic, Monolith) 3) SCR (no precious metal/ferric oxide, Ceramic, Monolith)	0.0055	0.07	0	0.00008		0.0055	
2013	Mercedes-Benz	GL 350 BLUETEC 4MATIC	LDT4	1) DOC (Pt+Pd, Ceramic, Monolith) 2) DPF (Pt+Pd, Ceramic, Monolith) 3) SCR (no precious metal/ferric oxide, Ceramic, Monolith)	0.0024	0.04	0	0		0.0024	
2013	Mercedes-Benz	GLK 250 BLUETEC 4MATIC	LDT2	1) DOC 2) DPF 3) SCR	0.00241	0.04	0	0		0.00241	
2013	Mercedes-Benz	S 350 BLUETEC 4MATIC	LDV	1) DOC (Pt+Pd, Ceramic, Monolith) 2) DPF (Pt+Pd, Ceramic, Monolith) 3) SCR (no precious metal/ferric oxide, Ceramic, Monolith)	0.0024	0.04	0	0		0.0024	
2014	Porsche	Cayenne Diesel	LDT3	1) DOC (Pt+Pd, Ceramic, Monolith) 2) DPF (Pt+Pd, Ceramic, Monolith) 3) SCR (Cu, Ceramic, Monolith)	0.012	0.21	0.004	0	0.012	0.012	0.0240
2011	VOLKSWAGEN	JETTA SPORTWAGEN	LDV	1) DOC (Pt+Pd+Rh, Metal, Monolith) 2) DPF (Pt+Pd, Ceramic, Monolith) 3) NOx Adsorber (Pt+Pd+Rh, Ceramic, Monolith)	0.0087	0.355	0.027	0.0003		0.0087	
2012	VOLKSWAGEN	Passat	LDV	1) DOC (Pt+Pd, Metal, Monolith) 2) DPF (Pt+Pd, Ceramic, Monolith) 3) SCR (CU, Ceramic, Monolith) 4) SCR (CU, Ceramic, Monolith)	0.0056	0.06	0.005	0.001	0.0092	0.0056	0.0148
2014	VOLKSWAGEN	JETTA SPORTWAGEN	LDV	1) DOC (Pt+Pd+Rh, Metal, Monolith) 2) Nox Adsorber (Pt+Pd+Rh, Ceramic, Monolith) 3) DPF (Pt+Pd, Ceramic, Monolith)	0.0081	0.3424	0.0136	0.0003	0.0081	0.0081	0.0162
2014	VOLKSWAGEN	Passat	LDV	1) DOC (Pt+Pd, Metal, Monolith) 2) DPF (Pt+Pd, Ceramic, Monolith) 3) SCR (CU, Ceramic, Monolith) 4) SCR (CU, Ceramic, Monolith)	0.0092	0.06	0.005	0.001	0.0092	0.0092	0.0087

Table A 2: Certification durability data for Light-Duty diesel vehicles MY 2011-2014: calculated multiplicative DFs at 160,000 km.

MY	*Manufacturer*	*Vehicle Model*	*Vehicle Class*	*After-treatment Devices*[12]	*CALCULATED*[13] *MULTIPLICATIVE DFs (160,000 km)*					
					CO	THC	NMHC	NOx	PM	CH4
2012	AUDI	Q7	LDT3/ LDT4	1) DOC (Pt+Pd, Ceramic, Monolith) 2) DPF (Pt+Pd, Ceramic, Monolith) 3) SCR (Cu, Ceramic, Monolith)	1.024	1.233	1.187	1.151	1.000	1.309
2014	AUDI	A8	LDV	1) DPF (Pt+Pd, Ceramic, Monolith) 2) DOC (Pt+Pd, Ceramic, Monolith) 3) SCR (Cu, Ceramic, Monolith)	1.012	1.067	1.058	1.050	1.062	1.000
2014	AUDI	Q7	LDT3	1) DOC (Pt+Pd, Ceramic, Monolith) 2) DPF (Pt+Pd, Ceramic, Monolith) 3) SCR (Cu, Ceramic, Monolith)	1.043	1.154	1.125	1.050	1.000	1.200
2014	AUDI	Q7	LDT4	1) DOC (Pt+Pd, Ceramic, Monolith) 2) DPF (Pt+Pd, Ceramic, Monolith) 3) SCR (Cu, Ceramic, Monolith)	1.090	1.154	1.125	1.050	1.000	1.000
2013	BMW	X5 xDrive35d	LDT4	1) DOC (Pt+Pd, Ceramic, Monolith) 2) DPF (Pt+Pd, Metal, Monolith) 3) SCR (no precious metal, Metal, Monolith)	1.148		1.208	1.090	1.000	
2014	BMW	328d xDrive Sports Wagon	LDV	1) DOC (Pt+Pd, Ceramic, Monolith) 2) DPF (Pt+Pd, Metal, Monolith) 3) SCR (no precious metal, Metal, Monolith) 4) Nox Adsorber (Pt+Pd+Rh, Ceramic, Monolith)	1.852		2.110	1.000	1.000	
2014	BMW	535d xDrive	LDV	1) DOC (Pt+Pd, Ceramic, Monolith) 2) DPF (Pt+Pd, Metal Monolith) 3) SCR (no precious metal, Metal Monolith) 4) NOx Adsorber (Pt+Pd+Rh, Ceramic, Monolith)	2.205		1.239	1.377	1.028	
2011	Mahindra	TR40	LDT4	1) DOC 2) DPF 3) SCR	1.008			1.000	1.000	
2013	Mercedes-Benz	E 350 BLUETEC	LDV	1) DOC (Pt+Pd, Ceramic, Monolith) 2) DPF (Pt+Pd, Ceramic, Monolith) 3) SCR (no precious metal/ferric oxide, Ceramic, Monolith)	1.014		1.054	1.000	1.007	

---

[12] After-treatment devices: Type (Precious metal, substrate material, substrate construction).

[13] Calculated according to $ADD\ DF = LIMIT - \frac{LIMIT}{MULT\ DF}$ [63], where ADD stands for additive, MULT for multiplicative and LIMIT is the corresponding emission limit:

LIMIT= EPA emission limits at 120,000 km, for consistency with EPA data and because this represents a conservative assumption (EPA limits are more stringent respect to Euro-5/6 limits (except that for CO) so that DFs are expected to be higher (except that for CO)).

2013	Mercedes-Benz	GL 350 BLUETEC	LDT4	1) DOC (Pt, Ceramic, Monolith) 2) DPF (Pt+Pd, Ceramic, Monolith) 3) SCR (no precious metal/ferric oxide, Ceramic, Monolith)	1.014		1.054	1.000	1.007	
2013	Mercedes-Benz	GL 350 BLUETEC 4MATIC	LDT4	1) DOC (Pt+Pd, Ceramic, Monolith) 2) DPF (Pt+Pd, Ceramic, Monolith) 3) SCR (no precious metal/ferric oxide, Ceramic, Monolith)	1.008		1.023	1.000	1.000	
2013	Mercedes-Benz	GLK 250 BLUETEC 4MATIC	LDT2	1) DOC 2) DPF 3) SCR	1.008		1.023	1.000	1.000	
2013	Mercedes-Benz	S 350 BLUETEC 4MATIC	LDV	1) DOC (Pt+Pd, Ceramic, Monolith) 2) DPF (Pt+Pd, Ceramic, Monolith) 3) SCR (no precious metal/ferric oxide, Ceramic, Monolith)	1.008		1.023	1.000	1.000	
2014	Porsche	Cayenne Diesel	LDT3	1) DOC (Pt+Pd, Ceramic, Monolith) 2) DPF (Pt+Pd, Ceramic, Monolith) 3) SCR (Cu, Ceramic, Monolith)	1.043	1.154	1.125	1.050	1.000	1.000
2011	VOLKSWAGEN	JETTA SPORTWAGEN	LDV	1) DOC (Pt+Pd+Rh, Metal, Monolith) 2) DPF (Pt+Pd, Ceramic, Monolith) 3) NOx Adsorber (Pt+Pd+Rh, Ceramic, Monolith)	1.076		1.088	1.474	1.026	
2012	VOLKSWAGEN	Passat	LDV	1) DOC (Pt+Pd, Metal, Monolith) 2) DPF (Pt+Pd, Ceramic, Monolith) 3) SCR (CU, Ceramic, Monolith) 4) SCR (CU, Ceramic, Monolith)	1.012	1.115	1.055	1.063	1.091	1.237
2014	VOLKSWAGEN	JETTA SPORTWAGEN	LDV	1) DOC (Pt+Pd+Rh, Metal, Monolith) 2) Nox Adsorber (Pt+Pd+Rh, Ceramic, Monolith) 3) DPF (Pt+Pd, Ceramic, Monolith)	1.073	1.127	1.081	1.193	1.026	1.000
2014	VOLKSWAGEN	Passat	LDV	1) DOC (Pt+Pd, Metal, Monolith) 2) DPF (Pt+Pd, Ceramic, Monolith) 3) SCR (CU, Ceramic, Monolith) 4) SCR (CU, Ceramic, Monolith)	1.012	1.065	1.093	1.063	1.091	1.343

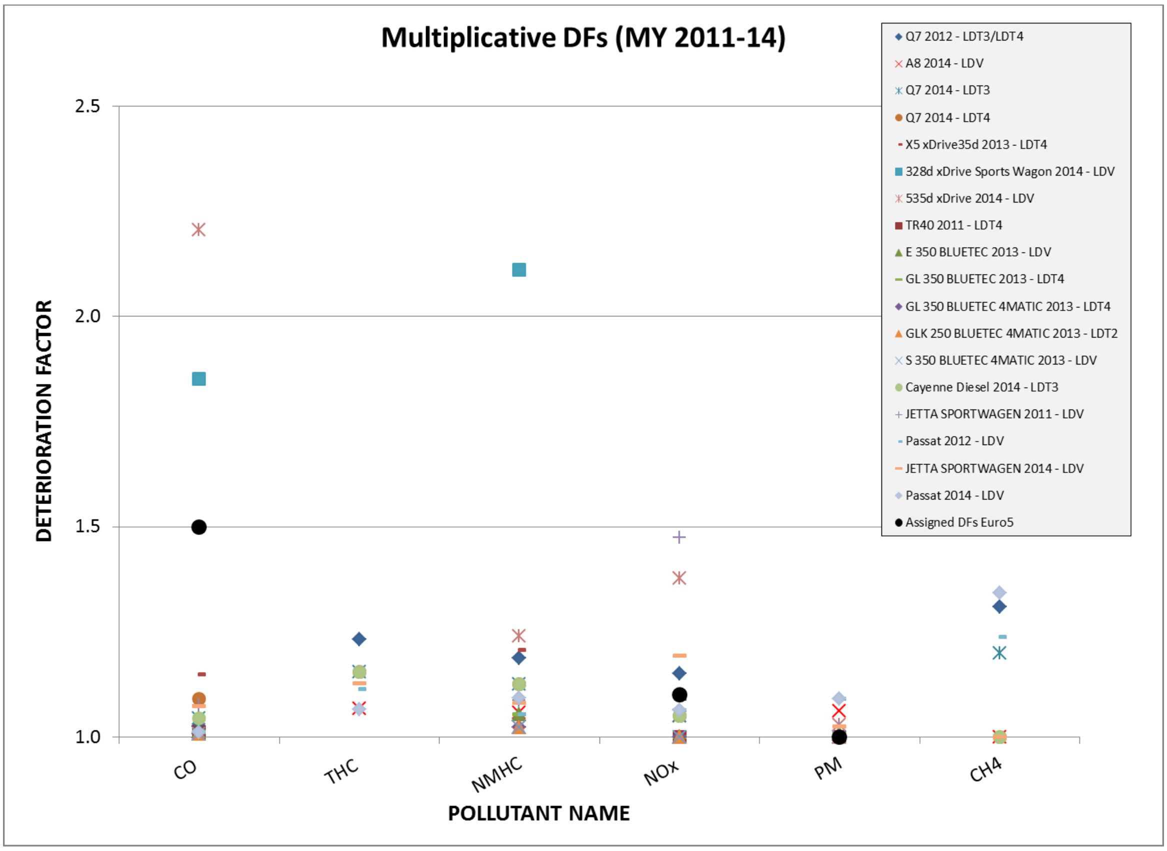


Figure A 1: Multiplicative DFs for diesel vehicles MY 2011-2014 at 160,000 km (100,000 mi).

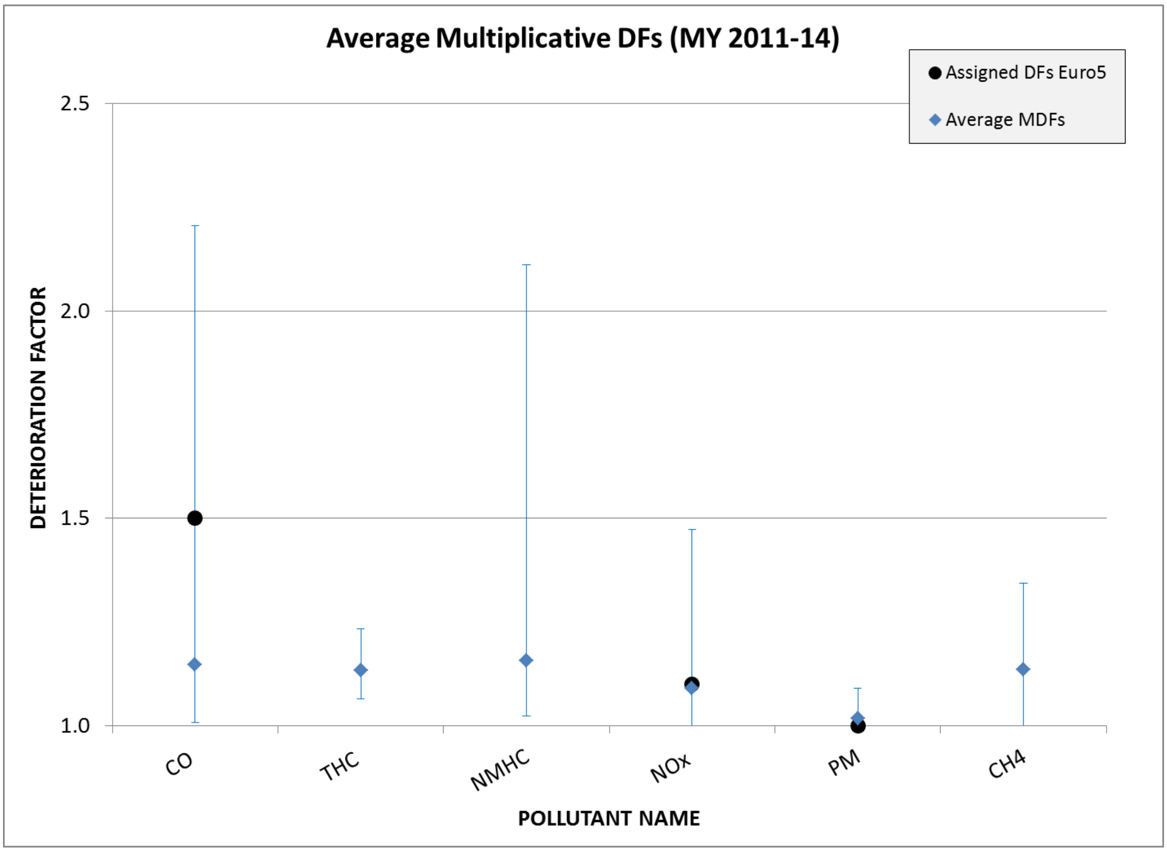


Figure A 2: Multiplicative DFs for diesel vehicles MY 2011-2014 at 160,000 km: Average values compared to Assigned DFs Euro 5.

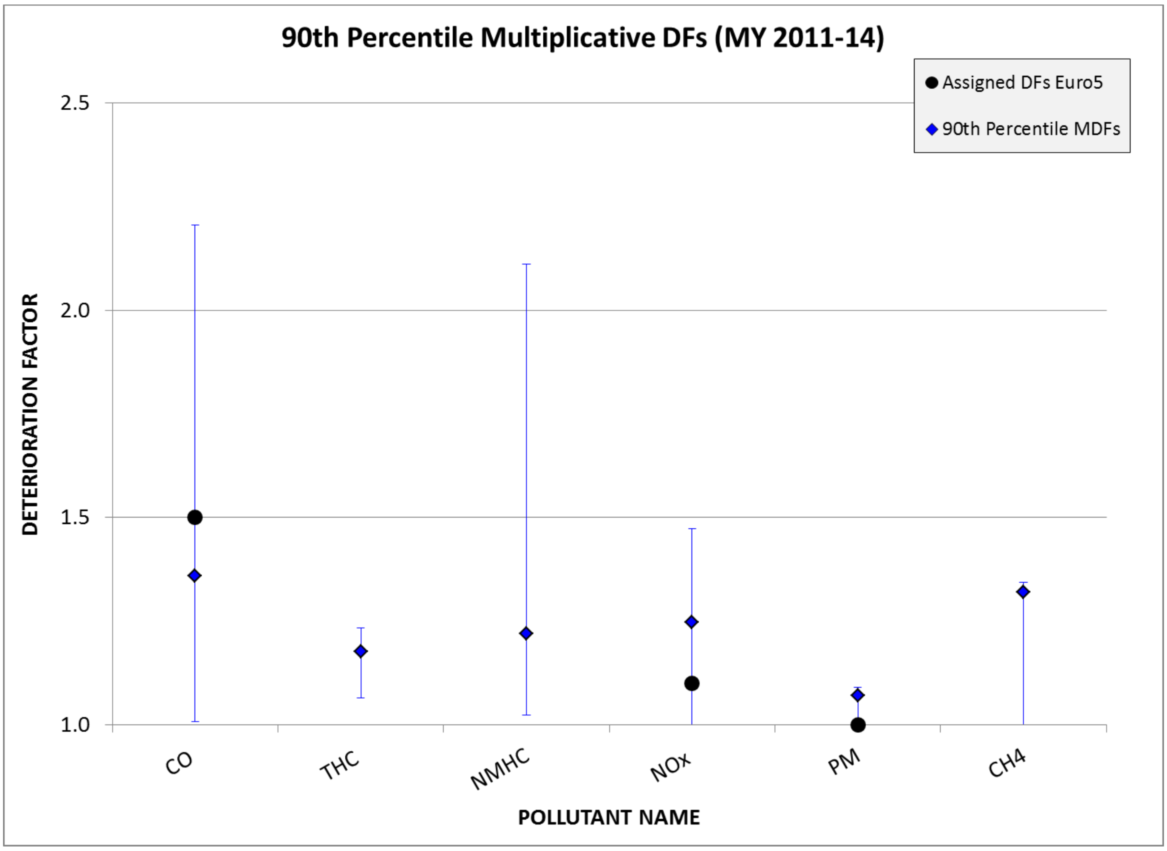


Figure A 3: Multiplicative DFs for diesel vehicles MY 2011-2014 at 160,000 km: 90th percentile compared to Assigned DFs Euro 5.

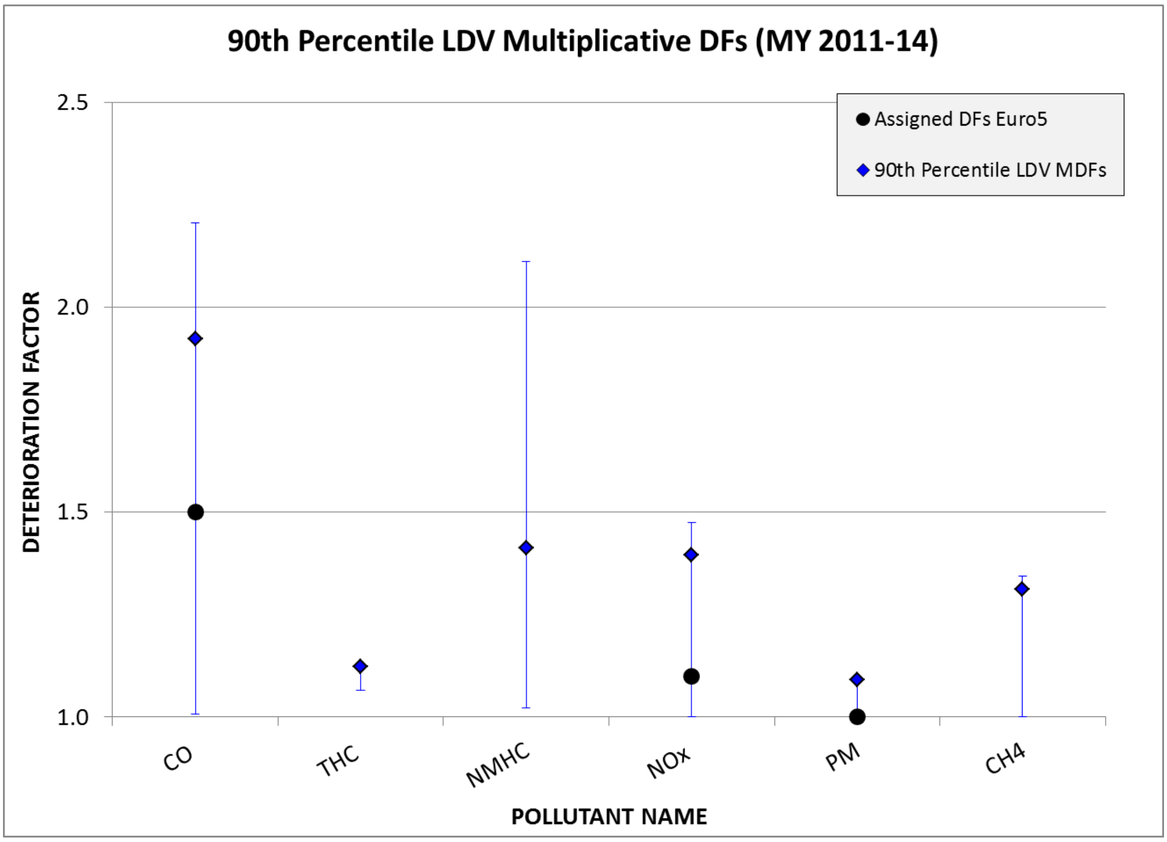


Figure A 4: Multiplicative DFs for diesel vehicles MY 2011-2014 at 160,000 km: 90th percentile values for LDVs.

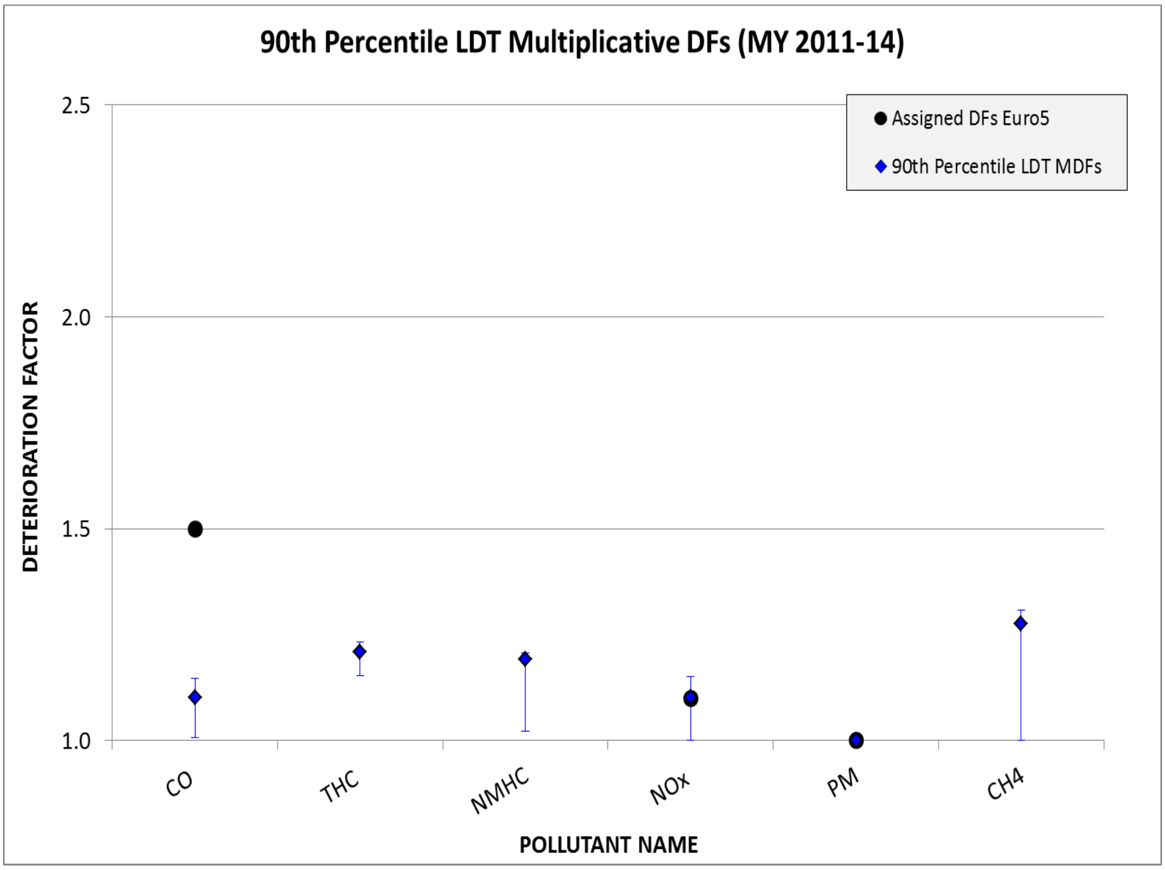


Figure A 5: Multiplicative DFs for diesel vehicles MY 2011-2014 at 160,000 km: 90th percentile values for LDTs.

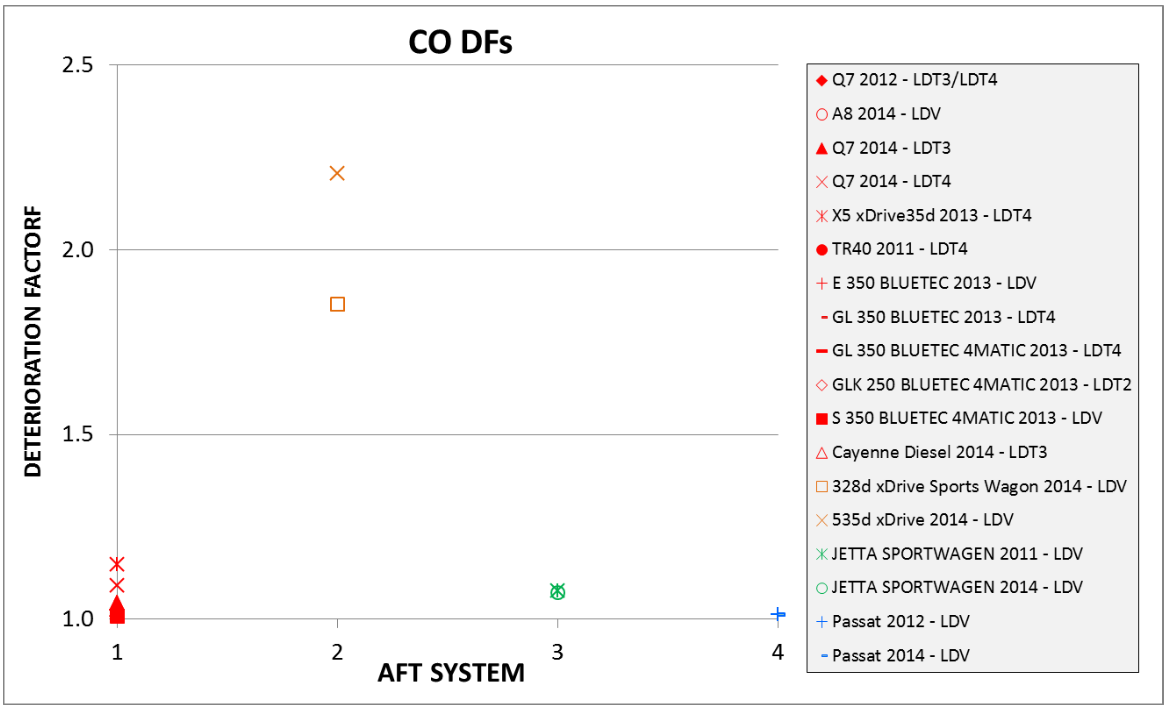


Figure A 6: CO multiplicative DFs for diesel vehicles MY 2011-2014 at 160,000 km: after-treatment system configuration 1) Doc+DPF+SCR; 2). Doc+DPF+SCR+LNT; 3) DOC+DPF+LNT; 4)DOC+DPF+SCR+SCR.

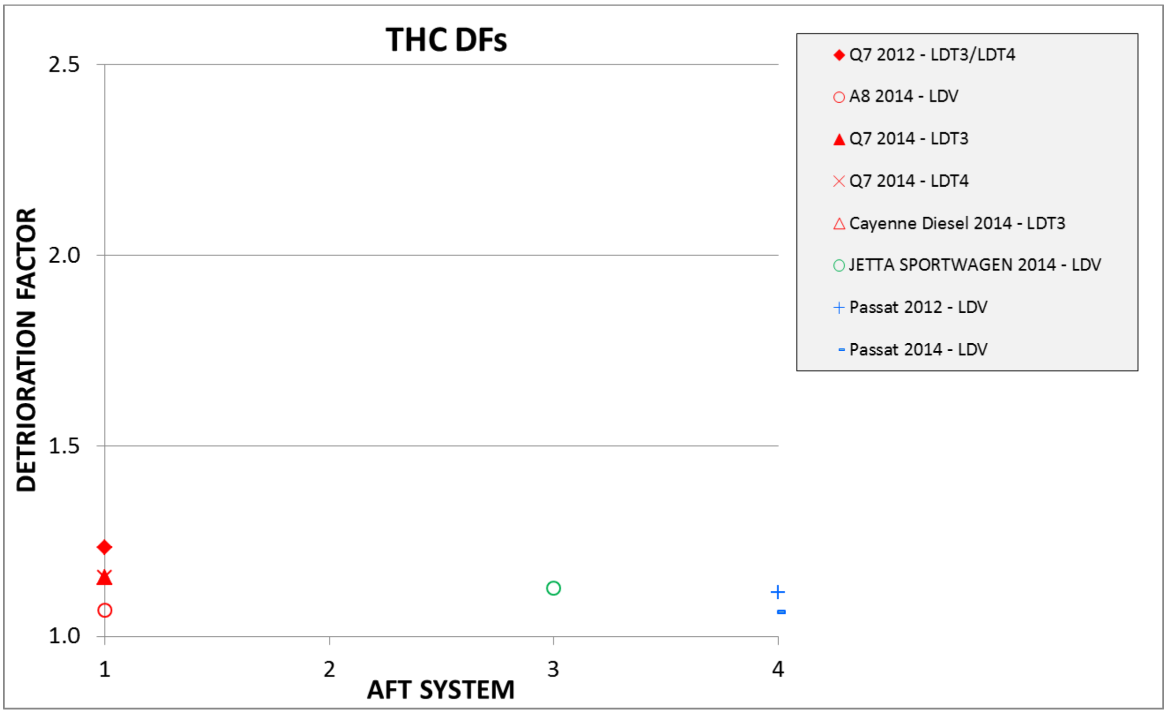


Figure A 7: THC multiplicative DFs for diesel vehicles MY 2011-2014 at 160,000 km: after-treatment system configuration 1) Doc+DPF+SCR; 2). Doc+DPF+SCR+LNT; 3) DOC+DPF+LNT; 4)DOC+DPF+SCR+SCR.

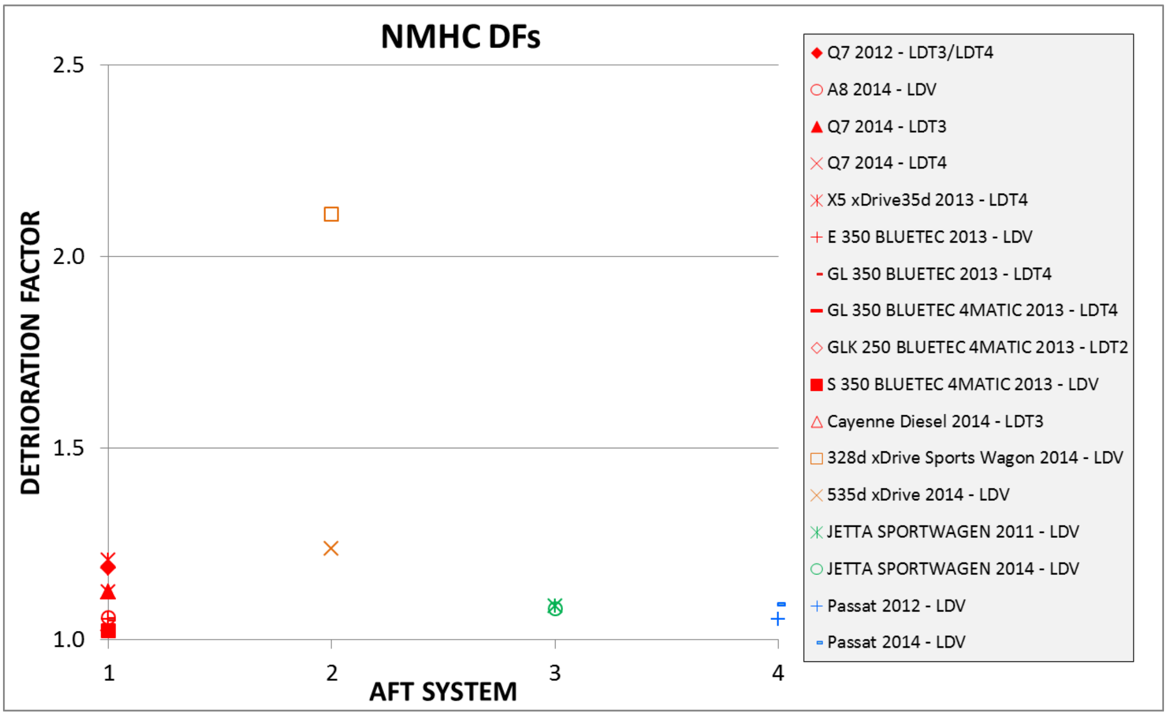


Figure A 8: NMHC multiplicative DFs for diesel vehicles MY 2011-2014 at 160,000 km: after-treatment system configuration 1) Doc+DPF+SCR; 2). Doc+DPF+SCR+LNT; 3) DOC+DPF+LNT; 4)DOC+DPF+SCR+SCR.

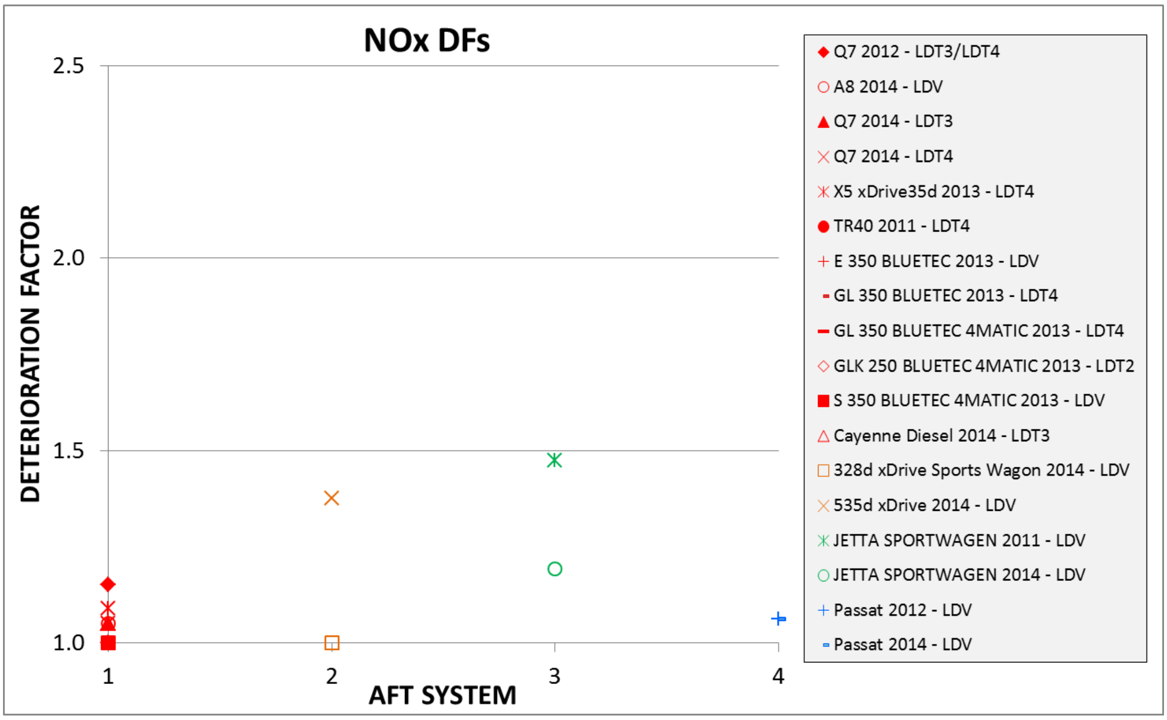


Figure A 9: NOx multiplicative DFs for diesel vehicles MY 2011-2014 at 160,000 km: after-treatment system configuration 1) Doc+DPF+SCR; 2). Doc+DPF+SCR+LNT; 3) DOC+DPF+LNT; 4)DOC+DPF+SCR+SCR.

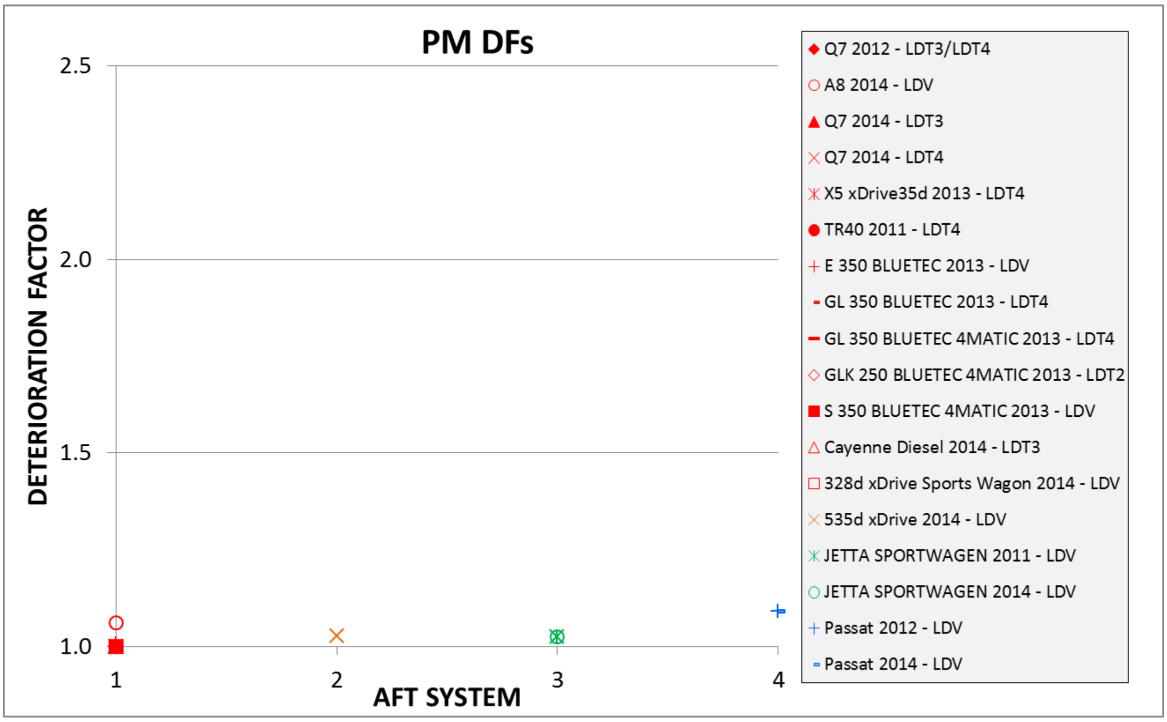


Figure A 10: PM multiplicative DFs for diesel vehicles MY 2011-2014 at 160,000 km: after-treatment system configuration 1) Doc+DPF+SCR; 2). Doc+DPF+SCR+LNT; 3) DOC+DPF+LNT; 4)DOC+DPF+SCR+SCR.

APPENDIX 2 - DFS FOR EURO 6-LIKE GASOLINE VEHICLES

Table A 3: Certification durability data for Light-Duty gasoline vehicles MY 2014: declared additive DFs at 120,000 mi (190,000 km).

MY	*Manufacturer*	*Vehicle Model*	*Hybrid Y/N*	*Vehicle Class*	*DECLARED ADDITIVE DFs [g/mi][14] (190,000 km)*						
					NMOG	CO	NOx	PM	CH4	NMHC[15]	THC[16]
2014	Chrysler	300	N	LDV	0.0000	0	0		0		
2014	BMW	328i xDrive	N	LDV	0.0139	0.659091	0.001973				
2014	Ferrari	458 Italia Spyder	N	LDV	0.0072	0.066667	0.002500		0.007167		
2014	BMW	535i xDrive Gran Turismo	N	LDV	0.0149	1.312500	0.002405				
2014	BMW	760Li	N	LDV	0.0111	1.049020	0.017369				
2014	LAMBORGHINI	834	N	LDV	0.0054	0.219167	0.003333		0.005167	0.005208	0.010375
2014	Porsche	911 Carrera 4S Cabriolet	N	LDV	0.0047	0.016667	0	0	0.004667	0.004487	0.009154
2014	AUDI	A6 quattro	N	LDV	0.0108	0.258333	0.010833		0.010333	0.010337	0.020670
2014	AUDI	A8	N	LDV	0.0073	0.983333	0.015833		0.006667	0.007051	0.013718
2014	BMW	Alpina B7 LWB xDrive	N	LDV	0.0111	1.049020	0.017369				
2014	AUDI	Audi A8 W12	N	LDV	0.0043	0	0	0	0.004083	0.004087	0.008170
2014	Mercedes-Benz	B 250	N	LDV	0.0056	0.108333	0.006667		0.005583	0.005369	0.010952
2014	VOLKSWAGEN	Beetle	N	LDV	0.0107	0.163333	0.001333	0	0	0.010256	0.010256
2014	Porsche	Boxster	N	LDV	0.0058	0.250000	0.003333	0	0.005833	0.005609	0.011442
2014	Porsche	Boxster S	N	LDV	0.0047	0.016667	0	0	0.005833	0.004487	0.010321
2014	SUBARU	BRZ	N	LDV	0.0105	0.632500	0.006583	0.000158		0.010048	
2014	Mercedes-Benz	C 250 (coupe)	N	LDV	0.0130	0.500000	0.011667		0.013000	0.012500	0.025500
2014	Kia	Cadenza	N	LDV	0.0074	0.175000	0.005000		0.007417	0.007131	0.014548
2014	CHEVROLET	CAMARO	N	LDV	0.0000						
2014	Mercedes-Benz	CL 550 4MATIC	N	LDV	0.0093	0	0			0	
2014	Mercedes-Benz	CL 600	N	LDV	0.0013	0.083333	0.004167		0.002833	0.002724	0.005558

---

[14] EPA website, Cars and Light Trucks, Annual Certification Test Results & Data [61].

[15] When not available, calculated based on the NMOG/NMHC ratio declared by the car manufacturer.

[16] Calculated as NMHC+METHANE values [62].

2014	BENTLEY	Continental GT	N	LDV	0.0063	0.150000	0.011667		0.007500	0.007212	0.014712
2014	BENTLEY	Continental GT	N	LDV	0.0050	0.575000	0.026667		0.011000	0.010577	0.021577
2014	CADILLAC	CTS WAGON	N	LDV	0.0000						
2014	Dodge	Dart	N	LDV	0.0000	0.341667	0.040833		0		
2014	Aston Martin	DB9	N	LDV	0.0028	0.241667	0.011667		0.010250	0	0
2014	Mercedes-Benz	E 350 4MATIC (coupe)	N	LDV	0.0075	0.159500	0		0.009500	0	0
2014	Mercedes-Benz	E 350 4MATIC (station wagon)	N	LDV	0.0110	0.325000	0.002500		0	0.018189	0
2014	HYUNDAI	Elantra GT	N	LDV	0.0074	0.416667	0.005833		0	0.014103	0
2014	Hyundai	Equus	N	LDV	0.0059	0.091667	0.006667		0.007500	0.007212	0.014712
2014	Ford	Escape AWD	N	LDV	0.0007	0.083333	0.021667			0.009054	
2014	Ford	ESCAPE FWD	N	LDV	0.0100	0.125000	0.010000			0.005048	
2014	LOTUS	EVORA	N	LDV	0.0103	0.800000	0.003333		0.005083		
2014	Ferrari	FF	N	LDV	0.0095	0.108333	0		0.001250		
2014	FORD	FLEX	N	LDV	0.0189	0.105000	0.002500			0.003205	
2014	Ford	FOCUS	N	LDV	0.0147	0	0.002500			0.002404	
2014	KIA	Forte ECO	N	LDV	0.0075	0	0		0	0	0
2014	Ford	Fusion FWD	N	LDV	0.0094	0.191667	0.013333			0.011859	
2014	Mercedes-Benz	GLK 350	N	LDV	0.0075	0.200000	0.015833		0	0.009455	0
2014	ACURA	ILX	N	LDV	0.0102	0.025000	0.000833		0	0.003365	0
2014	ACURA	ILX	N	LDV	0.0053	0	0.013333		0.002750	0.004247	0.006997
2014	SUBARU	IMPREZA AWD	N	LDV	0.0118	0.528862	0.022414		0	0	0
2014	INFINITI	INFINITI G37x Coupe AWD	N	LDV	0.0043	0.575000	0.026667			0.010577	
2014	INFINITI	INFINITI Q50S Q50 HYBRID SPORT AWD	Y	LDV	0.0024	0.241667	0.011667			0.009856	
2014	SCION	iQ	N	LDV	0.0052	0.500000	0.032500		0	0.012179	0
2014	VOLKSWAGEN	Jetta	N	LDV	0.0033	0.191667	0		0	0.004167	0
2014	VW	Jetta	N	LDV	0.0025	0.016667	0		0	0.003526	0.003526
2014	Mini	John Cooper Works All4 Countryman	N	LDV	0.0215	0.158333	0.011417				
2014	BUICK	LACROSSE	Y	LDV	0.0000						
2014	MITSUBISHI	LANCER EVOLUTION	N	LDV	0.0123	0.050000	0			0.007532	
2014	MITSUBISHI	LANCER SPORTBACK	N	LDV	0.0098	0.391667	0.025833			0.011538	

2014	BMW	M6 Convertible	N	LDV	0.0168	0.608333	0.030833				
2014	MAZDA	MAZDA3-4	N	LDV	0.0035	0.241667	0.011667			0	
2014	MAZDA	MAZDA6	N	LDV	0.0035	0.241667	0.011667			0	
2014	ACURA	MDX 4WD	N	LDV	0.0044	0.708333	0.008333		0.009750	0.009375	0.019125
2014	Mini	Mini Cooper Countryman	N	LDV	0.0178	1.183333	0.010000				
2014	MITSUBISHI	MIRAGE	N	LDV	0.0043	0.166667	0.000833			0.008654	
2014	Lincoln	MKT	N	LDV	0.0120	0.158333	0.010000			0.012660	
2014	Mercedes-Benz	ML 350 4MATIC	N	LDV	0.0110	0.241667	0.006667		0.001333	0.001282	0.002615
2014	McLaren	MP4-12C Coupe	N	LDV	0.0103	0.533333	0.002500		0.004583	0.004407	0.008990
2014	FORD	MUSTANG	N	LDV	0.0069	0.308333	0.010000			0.010337	
2014	MAZDA	MX-5	N	LDV	0.0127	0.141667	0.005833			0.008734	
2014	NISSAN	NISSAN GT-R	N	LDV	0.0043	0	0.005833			0.008494	
2014	NISSAN	NISSAN VERSA S	N	LDV	0.0037	0	0.005833			0.008494	0.017327
2014	SUBARU	OUTBACK AWD	N	LDV	0.0041	0.250000	0.008333		0.010000	0.009615	0.019615
2014	VOLKSWAGEN	Passat	N	LDV	0.0029	0.325000	0	0	0.004583	0.007452	0.012035
2014	VOLKSWAGEN	PASSAT CC 4MOTION	N	LDV	0.0078	0	0.007000		0.001417	0.004087	0.005503
2014	Ford	Police Interceptor Sedan FFV	N	LDV	0.0120	0.008333	0			0.004808	
2014	AUDI	Q5	N	LDV	0.0118	1.049020	0.017369	0	0	0	0
2014	MASERATI	QUATTROPORTE GTS	N	LDV	0.0103	0.600000	0.018333		0.022500		
2014	MASERATI	QUATTROPORTE S	N	LDV	0.0103	0.241667	0.011667		0.010250		
2014	AUDI	R8	N	LDV	0.0098	0.166917	0		0.003167	0.000721	0.003888
2014	AUDI	R8	N	LDV	0.0171	0.125000	0		0.001167	0.001122	0.002288
2014	AUDI	RS5	N	LDV	0.0090	0.216667	0.008333		0.007500	0.007212	0.014712
2014	Volvo	S60 T5 AWD	N	LDV	0.0132	0.066667	0		0.004167	0.004006	0.008173
2014	Mercedes-Benz	SL 63 AMG	N	LDV	0.0013	0.283333	0.015000		0.008667	0.003125	0.011792
2014	Kia	Sorento	N	LDV	0.0046	0.291667	0.013333		0.006083	0.011058	0.017141
2014	Kia	Sorento	N	LDV	0.0108	0.391667	0.025833		0	0.011538	0
2014	SCION	tC	N	LDV	0.0091	0.291667	0.013333		0.006083	0.011058	0.017141
2014	VOLKSWAGEN	Tiguan	N	LDV	0.0088	0.041667	0.030000	0	0	0.000641	0
2014	SUBARU	TRIBECA AWD	N	LDV	0.0144	0.150000	0.011667			0.007212	
2014	AUDI	TT COUPE QUATTRO	N	LDV	0.0088	0.091667	0.001667		0	0.003285	0

2014	Aston Martin	V8 VANTAGE S	N	LDV	0.0192	0.041667	0.001667		0	0.003846	0
2014	BUGATTI	Veyron Super Sport	N	LDV	0.0100	0	0		0	0.001442	0
2014	SRT	Viper	N	LDV	0.0000	0.508333	0.007500		0.020250		
2014	BMW	X3 xDrive28i	N	LDV	0.0215	0.491667	0.016667				
2014	BMW	X3 xDrive35i	N	LDV	0.0243	0.258333	0.001667				
2014	Volvo	XC60 T6 AWD	N	LDV	0.0103	0.633333	0.010000		0.007917	0.007933	0.015849
2014	Volvo	XC90 3.2 AWD	N	LDV	0.0097	0.416667	0.003333		0.004583	0.004407	0.008990
2014	Jaguar	XF	N	LDV	0.0078	0.225000	0.003333	0	0	0.014663	0
2014	JAGUAR	XF-R	N	LDV	0.0043	0.258333	0	0	0	0.007131	0
2014	Jaguar	XJ 3.0	N	LDV	0.0018	0.477667	0.015167	0	0	0.011963	0
2014	Jaguar	XJ Supercharged	N	LDV	0.0018	0.491667	0.016667	0	0	0.009455	0
2014	TOYOTA	YARIS	N	LDV	0.0050	0	0		0	0	0
2014	BMW	Z4 sDrive35is	N	LDV	0.0111	0	0				
2014	Jeep	Grand Cherokee	N	LDT4	0.0000	0.025000	0.000833		0		
2014	INFINITI	INFINITI QX56 4WD	N	LDT4	0.0083	0.175000	0			0.006651	
2014	AUDI	Q7	N	LDT4	0.0234	0.425000	0.013333		0	0.008013	0
2014	Land Rover	Range Rover Sport	N	LDT4	0.0103	0.121667	0		0.001167	0.001122	0.002288
2014	Land Rover	Range Rover Supercharged	N	LDT4	0.0008	1.535915	0.019444	0	0	0	0
2014	VW	Touareg	Y	LDT4	0.0012	0.208333	0.024167	0	0	0.002965	0
2014	VW	Touareg	Y	LDT4	0.0012	0.265917	0.006833		0	0.010777	0
2014	BMW	X5 xDriveM	N	LDT4	0.0168	0.458333	0.006667				
2014	Porsche	Cayenne	N	LDT3	0.0075	0.275000	0.003333	0	0	0.008974	0
2014	Porsche	Cayenne GTS	N	LDT3	0.0042	0.241667	0.006667	0	0.001333	0.001282	0.002615
2014	Porsche	Cayenne Turbo	N	LDT3	0.0000	0.316667	0.005833	0	0.006000	0.006010	0.012010
2014	CHEVROLET	CC10903	N	LDT3	0.0033	0.141667	0.001667		0.005000	0.004808	0.009808
2014	CHEVROLET	CC10906	N	LDT3	0.0115	0	0		0	0	0
2014	Ford	Explorer Police FFV, AWD	N	LDT3	0.0120	0.041667	0.001667			0.002324	
2014	GMC	TC10906	N	LDT3	0.0115	0.028333	0.002333		0.006917	0.006651	0.013567
2014	VOLKSWAGEN	Touareg	N	LDT3	0.0069	0.208333	0.009167	0	0	0	0
2014	Ford	Escape AWD	N	LDT2	0.0007	0.150000	0.011667			0.007212	
2014	Ford	Escape AWD	N	LDT2	0.0000	0.058333	0.006667			0.009776	

2014	Ford	Explorer FWD	N	LDT2	0.0031	0	0.010000			0.004167	
2014	SUBARU	FORESTER	N	LDT2	0.0112	0.503425	0.009763	0		0	
2014	Mercedes-Benz	GLK 350 4MATIC	N	LDT2	0.0075	1.535915	0.019444		0	0	0
2014	INFINITI	INFINITI FX37 AWD	N	LDT2	0.0034	0.058333	0.016667			0.004167	
2014	INFINITI	INFINITI FX50 AWD	N	LDT2	0.0040	0.391667	0.025833			0.011538	
2014	NISSAN	NISSAN MURANO CrossCabriolet BASE	N	LDT2	0.0015	0.270000	0.019167			0.013886	
2014	HONDA	ODYSSEY TOURING	N	LDT2	0.0203	0.844167	0.011667		0.019167	0.018429	0.037596
2014	MITSUBISHI	OUTLANDER 4WD	N	LDT2	0.0098	0.503425	0.009763			0	
2014	MITSUBISHI	OUTLANDER 4WD	N	LDT2	0.0058	1.954064	0.015346			0	
2014	MITSUBISHI	OUTLANDER 4WD	N	LDT2	0.0237	0.050000	0.004167			0.009856	
2014	AUDI	Q5 Hybrid	Y	LDT2	0.0083	0	0	0	0	0	0
2014	Kia	Sedona	N	LDT2	0.0046	0.050000	0.000833		0	0	0
2014	Mazda	CX-5	N	LDT1	0.0153	0.340917	0.002833			0.005689	
2014	Mazda	CX-5	N	LDT1	0.0074	0.300000	0.016667			0.000641	
2014	SUBARU	OUTBACK WAGON AWD	N	LDT1	0.0124	0	0			0	
2014	MITSUBISHI	OUTLANDER SPORT 4WD	N	LDT1	0.0098	0	0.009167			0.009295	
2014	Jeep	Patriot 2wd	N	LDT1	0.0000	0	0.007000		0.001417		
2014	Jeep	Patriot 4wd	N	LDT1	0.0000	0	0.007000		0.001417		

Table A 4: Certification durability data for Light-Duty gasoline vehicles MY 2014: calculated multiplicative DFs at 160,000 km.

MY	Manufacturer	Vehicle Model	Hybrid Y/N	Vehicle Class	CALCULATED[17] MULTIPLICATIVE DFs (160,000 km)					
					CO	THC[18]	NMHC	NOx	PM	CH4
2014	Chrysler	300	N	LDV	1.000	1.000	1.000			
2014	BMW	328i xDrive	N	LDV	1.232		1.035			
2014	Ferrari	458 Italia Spyder	N	LDV	1.016	1.314	1.037			
2014	BMW	535i xDrive Gran Turismo	N	LDV	1.600		1.043			
2014	BMW	760Li	N	LDV	1.428		1.424			
2014	LAMBORGHINI	834	N	LDV	1.055	1.115	1.050		1.050	1.069
2014	Porsche	911 Carrera 4S Cabriolet	N	LDV	1.004	1.184	1.000	1.000	1.043	1.060
2014	AUDI	A6 quattro	N	LDV	1.066	1.525	1.183		1.104	1.147
2014	AUDI	A8	N	LDV	1.306	1.286	1.292		1.069	1.093
2014	BMW	Alpina B7 LWB xDrive	N	LDV	1.428		1.424			
2014	AUDI	Audi A8 W12	N	LDV	1.000	1.158	1.000	1.000	1.039	1.053
2014	Mercedes-Benz	B 250	N	LDV	1.026	1.229	1.105		1.052	1.073
2014	VOLKSWAGEN	Beetle	N	LDV	1.040	1.000	1.019	1.000	1.103	1.068
2014	Porsche	Boxster	N	LDV	1.063	1.241	1.050	1.000	1.054	1.077
2014	Porsche	Boxster S	N	LDV	1.004	1.241	1.000	1.000	1.043	1.068
2014	SUBARU	BRZ	N	LDV	1.177		1.104	1.016	1.101	
2014	Mercedes-Benz	C 250 (coupe)	N	LDV	1.135	1.765	1.200		1.129	1.188
2014	Kia	Cadenza	N	LDV	1.043	1.328	1.077		1.070	1.099
2014	CHEVROLET	CAMARO	N	LDV						
2014	Mercedes-Benz	CL 550 4MATIC	N	LDV	1.000		1.000		1.000	
2014	Mercedes-Benz	CL 600	N	LDV	1.020	1.104	1.063		1.026	1.036

---

[17] Calculated according to $ADD\ DF = LIMIT - \frac{LIMIT}{MULT\ DF}$ [63], where ADD stands for additive, MULT for multiplicative and LIMIT is the corresponding emission limit: LIMIT= EPA emission limits at 120,000 km, for consistency with EPA data and because this represents a conservative assumption (EPA limits are more stringent respect to Euro-5/6 limits (except that for CO) so that DFs are expected to be higher (except that for CO)).

[18] Euro-6 emission limit was considered as reference for THC and NMHC as not available from manufacturers' certification data.

2014	BENTLEY	Continental GT	N	LDV	1.037	1.333	1.200		1.071	1.101
2014	BENTLEY	Continental GT	N	LDV	1.159	1.000	1.615		1.107	1.155
2014	CADILLAC	CTS WAGON	N	LDV						
2014	Dodge	Dart	N	LDV	1.000	1.000	1.000			
2014	Aston Martin	DB9	N	LDV	1.061	1.519	1.200		1.000	1.000
2014	Mercedes-Benz	E 350 4MATIC (coupe)	N	LDV	1.039	1.463	1.000		1.000	1.000
2014	Mercedes-Benz	E 350 4MATIC (station wagon)	N	LDV	1.084	1.000	1.037		1.199	1.000
2014	HYUNDAI	Elantra GT	N	LDV	1.110	1.000	1.091		1.148	1.000
2014	Hyundai	Equus	N	LDV	1.022	1.333	1.105		1.071	1.101
2014	Ford	Escape AWD	N	LDV	1.020		1.448		1.090	
2014	Ford	ESCAPE FWD	N	LDV	1.031		1.167		1.048	
2014	LOTUS	EVORA	N	LDV	1.235	1.204	1.050			
2014	Ferrari	FF	N	LDV	1.026	1.043	1.000			
2014	FORD	FLEX	N	LDV	1.026		1.037		1.030	
2014	Ford	FOCUS	N	LDV	1.000		1.037		1.022	
2014	KIA	Forte ECO	N	LDV	1.000	1.000	1.000		1.000	1.000
2014	Ford	Fusion FWD	N	LDV	1.048		1.235		1.121	
2014	Mercedes-Benz	GLK 350	N	LDV	1.050	1.000	1.292		1.095	1.000
2014	ACURA	ILX	N	LDV	1.006	1.000	1.012		1.032	1.000
2014	ACURA	ILX	N	LDV	1.000	1.101	1.235		1.040	1.045
2014	SUBARU	IMPREZA AWD	N	LDV	1.144		1.471			1.000
2014	INFINITI	INFINITI G37x Coupe AWD	N	LDV	1.000		1.000		1.107	
2014	INFINITI	INFINITI Q50S Q50 HYBRID SPORT AWD	Y	LDV	1.000		1.000		1.099	
2014	SCION	iQ	N	LDV	1.135	1.000	1.867		1.125	1.000
2014	VOLKSWAGEN	Jetta	N	LDV	1.048	1.000	1.000		1.040	1.000
2014	VW	Jetta	N	LDV	1.004	1.000	1.000		1.033	1.022
2014	Mini	John Cooper Works All4 Countryman	N	LDV	1.168		1.201			
2014	BUICK	LACROSSE	Y	LDV						
2014	MITSUBISHI	LANCER EVOLUTION	N	LDV	1.012		1.000		1.074	
2014	MITSUBISHI	LANCER SPORTBACK	N	LDV	1.103		1.585		1.118	

2014	BMW	M6 Convertible	N	LDV	1.782		1.500			
2014	MAZDA	MAZDA3-4	N	LDV	1.061		1.200		1.000	
2014	MAZDA	MAZDA6	N	LDV	1.061		1.200		1.000	
2014	ACURA	MDX 4WD	N	LDV	1.203	1.481	1.135		1.094	1.135
2014	Mini	Mini Cooper Countryman	N	LDV	1.178		1.624			
2014	MITSUBISHI	MIRAGE	N	LDV	1.041		1.012		1.086	
2014	Lincoln	MKT	N	LDV	1.039		1.167		1.131	
2014	Mercedes-Benz	ML 350 4MATIC	N	LDV	1.061	1.047	1.105		1.012	1.017
2014	McLaren	MP4-12C Coupe	N	LDV	1.145	1.180	1.037		1.042	1.059
2014	FORD	MUSTANG	N	LDV	1.079		1.167		1.104	1.000
2014	MAZDA	MX-5	N	LDV	1.035		1.091		1.087	
2014	NISSAN	NISSAN GT-R	N	LDV	1.000		1.000		1.084	
2014	NISSAN	NISSAN VERSA S	N	LDV	1.000		1.000		1.084	1.121
2014	SUBARU	OUTBACK AWD	N	LDV	1.063		1.135			1.139
2014	VOLKSWAGEN	Passat	N	LDV	1.084	1.180	1.000	1.000	1.073	1.081
2014	VOLKSWAGEN	PASSAT CC 4MOTION	N	LDV	1.000	1.050	1.111		1.039	1.035
2014	Ford	Police Interceptor Sedan FFV	N	LDV	1.002		1.000		1.046	
2014	AUDI	Q5	N	LDV	1.333	1.000	1.330	1.000	1.000	1.000
2014	MASERATI	QUATTROPORTE GTS	N	LDV	1.167	4.000	1.355			
2014	MASERATI	QUATTROPORTE S	N	LDV	1.061	1.519	1.200			
2014	AUDI	R8	N	LDV	1.041	1.011	1.000		1.007	1.025
2014	AUDI	R8	N	LDV	1.031	1.040	1.000		1.010	1.014
2014	AUDI	RS5	N	LDV	1.054	1.333	1.135		1.071	1.101
2014	Volvo	S60 T5 AWD	N	LDV	1.016	1.161	1.000		1.038	1.053
2014	Mercedes-Benz	SL 63 AMG	N	LDV	1.072	1.406	1.273		1.029	1.079
2014	Kia	Sorento	N	LDV	1.075	1.254	1.235		1.112	1.119
2014	Kia	Sorento	N	LDV	1.103	1.000	1.585		1.118	1.000
2014	SCION	tC	N	LDV	1.075	1.254	1.235		1.112	1.119
2014	VOLKSWAGEN	Tiguan	N	LDV	1.010	1.000	1.750	1.000	1.006	1.000
2014	SUBARU	TRIBECA AWD	N	LDV	1.037		1.200		1.071	1.000
2014	AUDI	TT COUPE QUATTRO	N	LDV	1.022	1.000	1.024		1.031	1.000

2014	Aston Martin	V8 VANTAGE S	N	LDV	1.010	1.000	1.024		1.036	1.000
2014	BUGATTI	Veyron Super Sport	N	LDV	1.000	1.000	1.000		1.013	1.000
2014	SRT	Viper	N	LDV	1.000	1.000	1.000			
2014	BMW	X3 xDrive28i	N	LDV	1.168		1.201			
2014	BMW	X3 xDrive35i	N	LDV	2.264		1.357			
2014	Volvo	XC60 T6 AWD	N	LDV	1.178	1.553	1.167		1.078	1.109
2014	Volvo	XC90 3.2 AWD	N	LDV	1.110	1.933	1.050		1.042	1.059
2014	Jaguar	XF	N	LDV	1.057	1.000	1.050	1.000	1.155	1.000
2014	JAGUAR	XF-R	N	LDV	1.066	1.000	1.000	1.000	1.070	1.000
2014	Jaguar	XJ 3.0	N	LDV	1.128	1.000	1.277	1.000	1.123	1.000
2014	Jaguar	XJ Supercharged	N	LDV	1.133	1.000	1.313	1.000	1.095	1.000
2014	TOYOTA	YARIS	N	LDV	1.000	1.000	1.000		1.000	1.000
2014	BMW	Z4 sDrive35is	N	LDV	1.428		1.424			
2014	Jeep	Grand Cherokee	N	LDT4	1.000	1.000	1.000			
2014	INFINITI	INFINITI QX56 4WD	N	LDT4	1.000		1.000		1.048	
2014	AUDI	Q7	N	LDT4	1.113	1.000	1.235		1.059	1.000
2014	Land Rover	Range Rover Sport	N	LDT4	1.030	1.040	1.000		1.008	1.011
2014	Land Rover	Range Rover Supercharged	N	LDT4	1.577	1.000	1.385	1.000	1.000	1.000
2014	VW	Touareg	Y	LDT4	1.052	1.000	1.527	1.000	1.021	1.000
2014	VW	Touareg	Y	LDT4	1.068	1.000	1.108		1.080	1.000
2014	BMW	X5 xDriveM	N	LDT4	1.782		1.500			
2014	Porsche	Cayenne	N	LDT3	1.070	1.000	1.050	1.000	1.066	1.000
2014	Porsche	Cayenne GTS	N	LDT3	1.061	1.047	1.105	1.000	1.009	1.013
2014	Porsche	Cayenne Turbo	N	LDT3	1.082	1.250	1.091	1.000	1.043	1.061
2014	CHEVROLET	CC10903	N	LDT3	1.035	1.200	1.024		1.034	1.049
2014	CHEVROLET	CC10906	N	LDT3	1.000	1.000	1.000		1.000	1.000
2014	Ford	Explorer Police FFV, AWD	N	LDT3	1.010		1.024		1.016	
2014	GMC	TC10906	N	LDT3	1.007	1.130	1.034		1.048	1.069
2014	VOLKSWAGEN	Touareg	N	LDT3	1.052	1.000	1.151	1.000	1.000	1.000
2014	Ford	Escape AWD	N	LDT2	1.037		1.200		1.043	
2014	Ford	Escape AWD	N	LDT2	1.014		1.105		1.060	

2014	Ford	Explorer FWD	N	LDT2	1.000		1.167		1.025	
2014	SUBARU	FORESTER	N	LDT2	1.136		1.162	1.000	1.000	
2014	Mercedes-Benz	GLK 350 4MATIC	N	LDT2	1.577	1.000	1.385		1.000	1.000
2014	INFINITI	INFINITI FX37 AWD	N	LDT2	1.000		1.000		1.025	
2014	INFINITI	INFINITI FX50 AWD	N	LDT2	1.000		1.000		1.071	
2014	NISSAN	NISSAN MURANO CrossCabriolet BASE	N	LDT2	1.000		1.000		1.087	
2014	HONDA	ODYSSEY TOURING	N	LDT2	1.252	2.769	1.200		1.119	1.171
2014	MITSUBISHI	OUTLANDER 4WD	N	LDT2	1.136		1.162		1.000	
2014	MITSUBISHI	OUTLANDER 4WD	N	LDT2	1.870		1.281		1.000	
2014	MITSUBISHI	OUTLANDER 4WD	N	LDT2	1.012		1.063		1.060	
2014	AUDI	Q5 Hybrid	Y	LDT2	1.000	1.000	1.000	1.000	1.000	1.000
2014	Kia	Sedona	N	LDT2	1.012	1.000	1.012		1.000	1.000
2014	Mazda	CX-5	N	LDT1	1.088		1.042		1.041	
2014	Mazda	CX-5	N	LDT1	1.077		1.313		1.004	
2014	SUBARU	OUTBACK WAGON AWD	N	LDT1	1.000		1.000		1.000	1.000
2014	MITSUBISHI	OUTLANDER SPORT 4WD	N	LDT1	1.000		1.151		1.069	
2014	Jeep	Patriot 2wd	N	LDT1	1.000	1.000	1.000			
2014	Jeep	Patriot 4wd	N	LDT1	1.000	1.000	1.000			

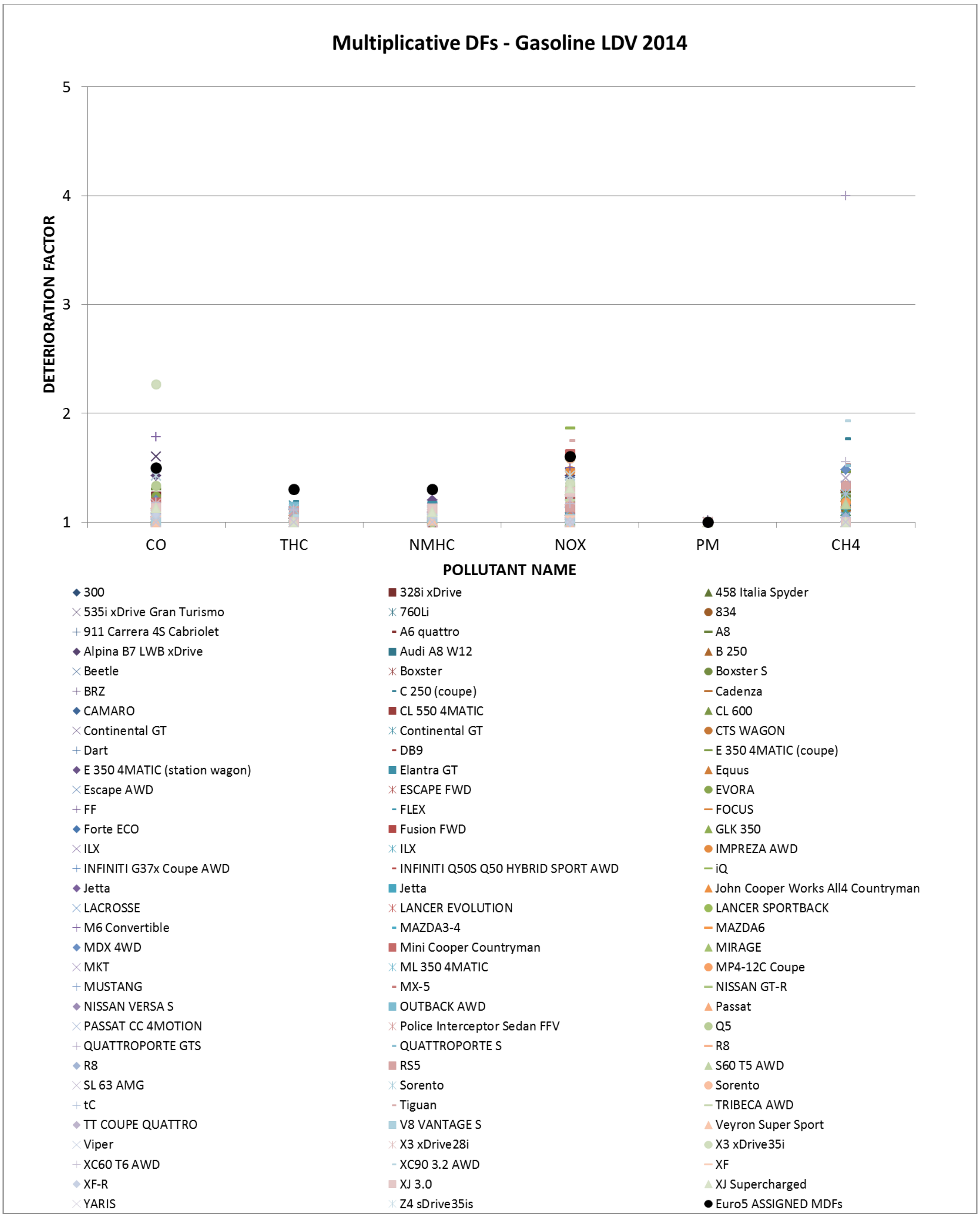


Figure A 11: Multiplicative DFs for gasoline LDVs MY 2014 at 160,000 km (100,000 mi).

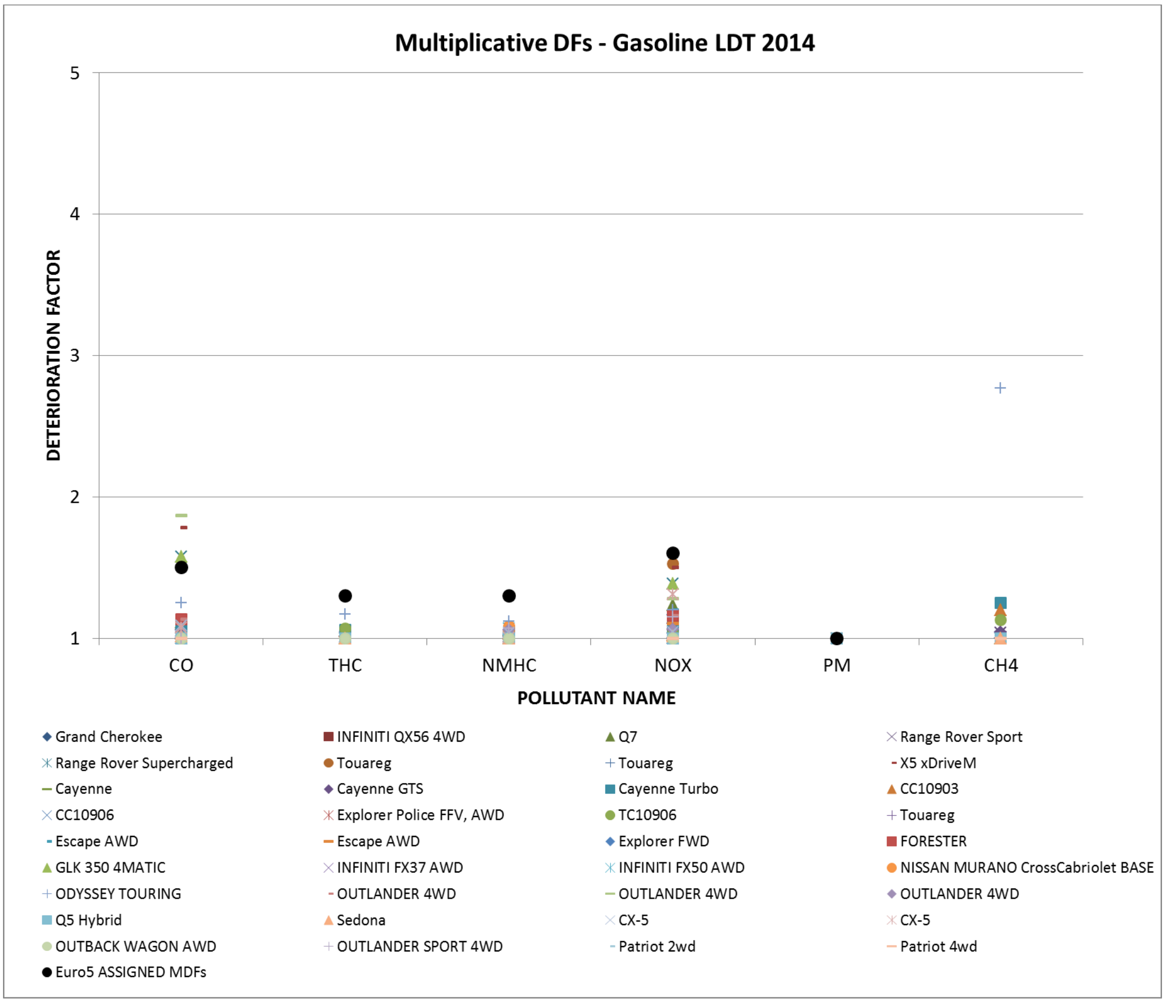


Figure A 12: Multiplicative DFs for gasoline LDTs MY 2014 at 160,000 km (100,000 mi).

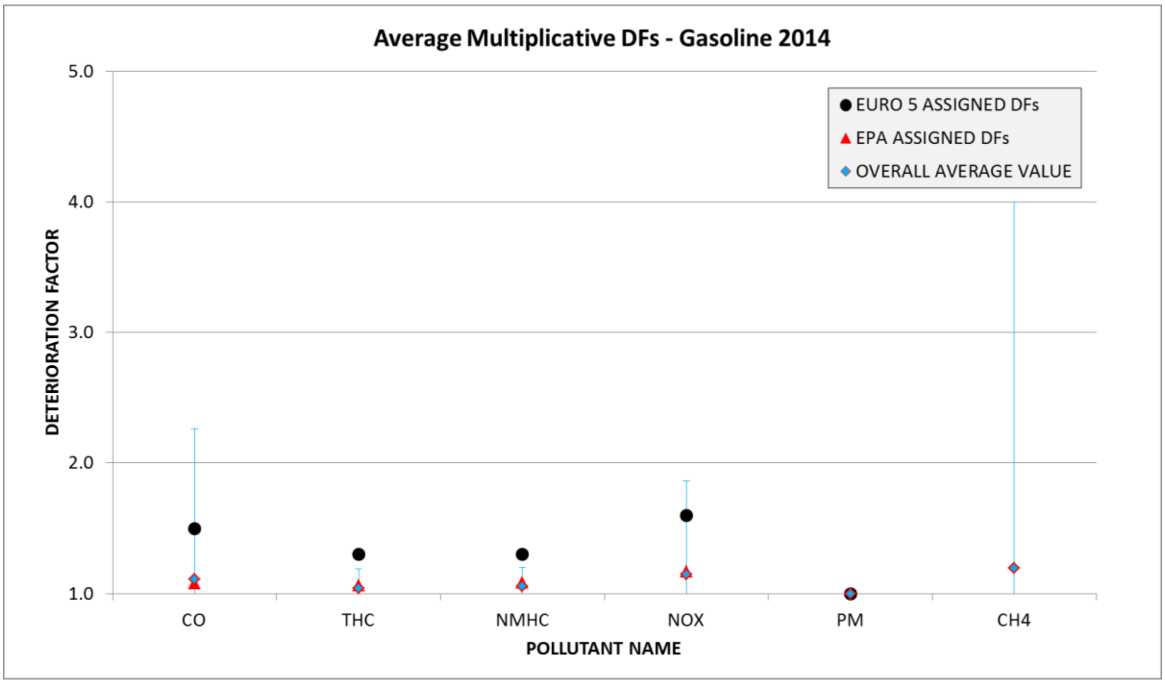


Figure A 13: Multiplicative DFs for gasoline vehicles MY 2014 at 160,000 km: Average values compared to Assigned DFs Euro 5.

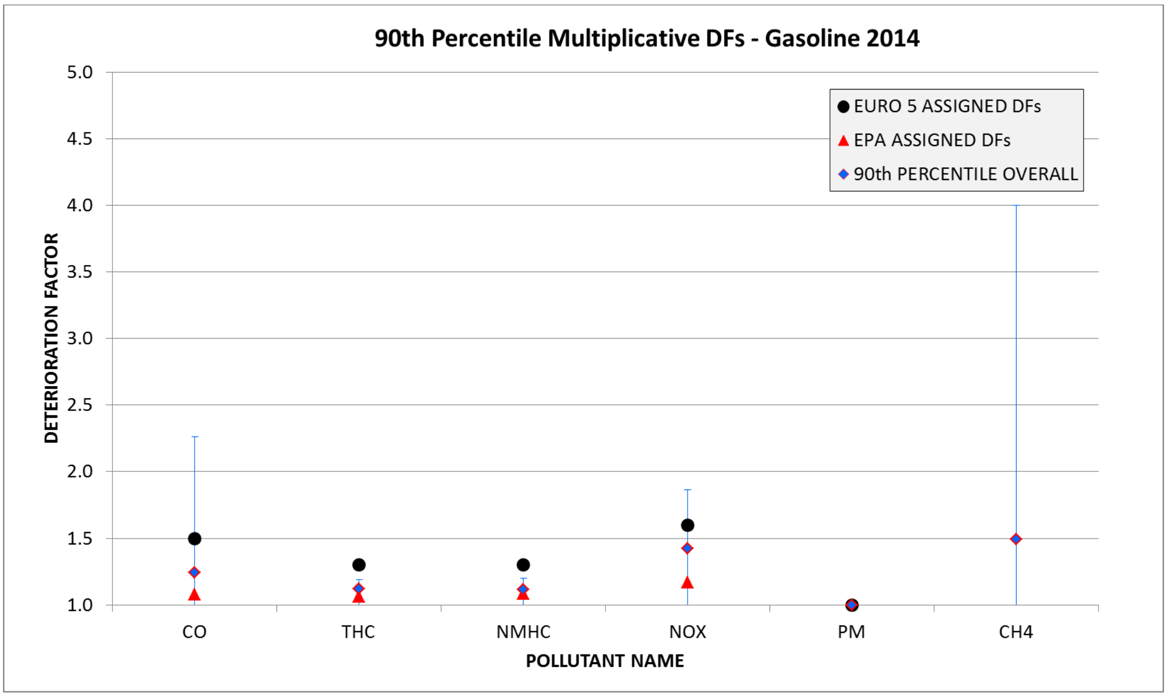


Figure A 14: Multiplicative DFs for gasoline vehicles MY 2014 at 160,000 km: 90th percentile compared to Assigned DFs Euro 5.

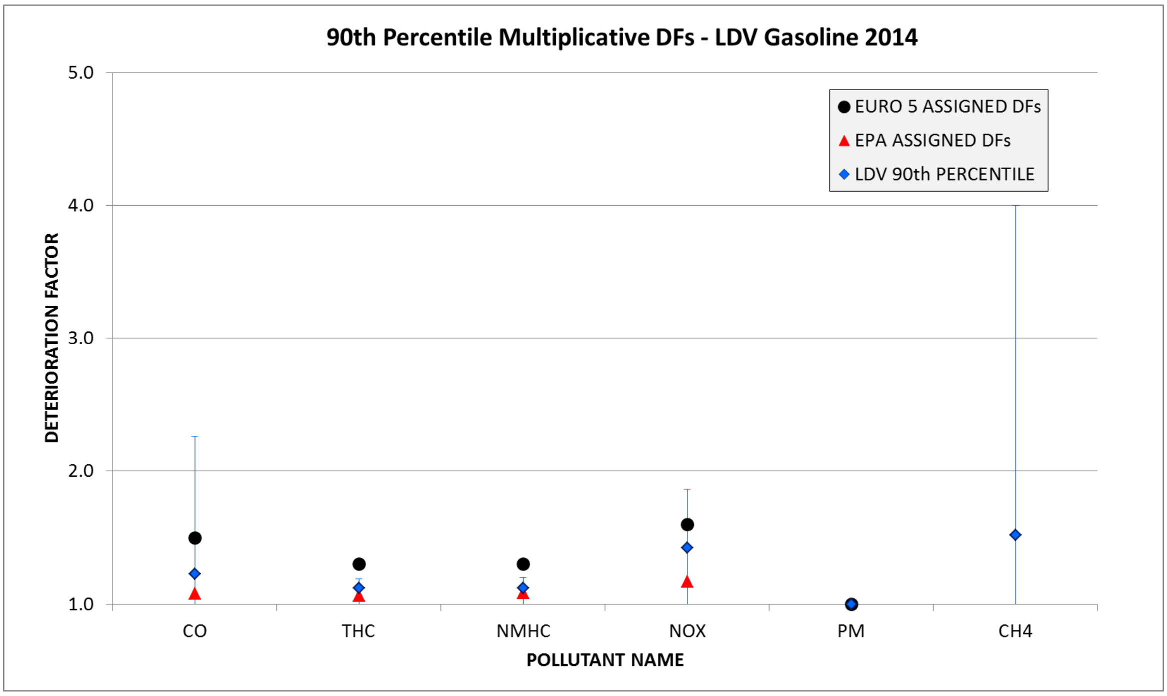


Figure A 15: Multiplicative DFs for gasoline vehicles MY 2014 at 160,000 km: 90th percentile for LDVs compared to Assigned DFs Euro 5.

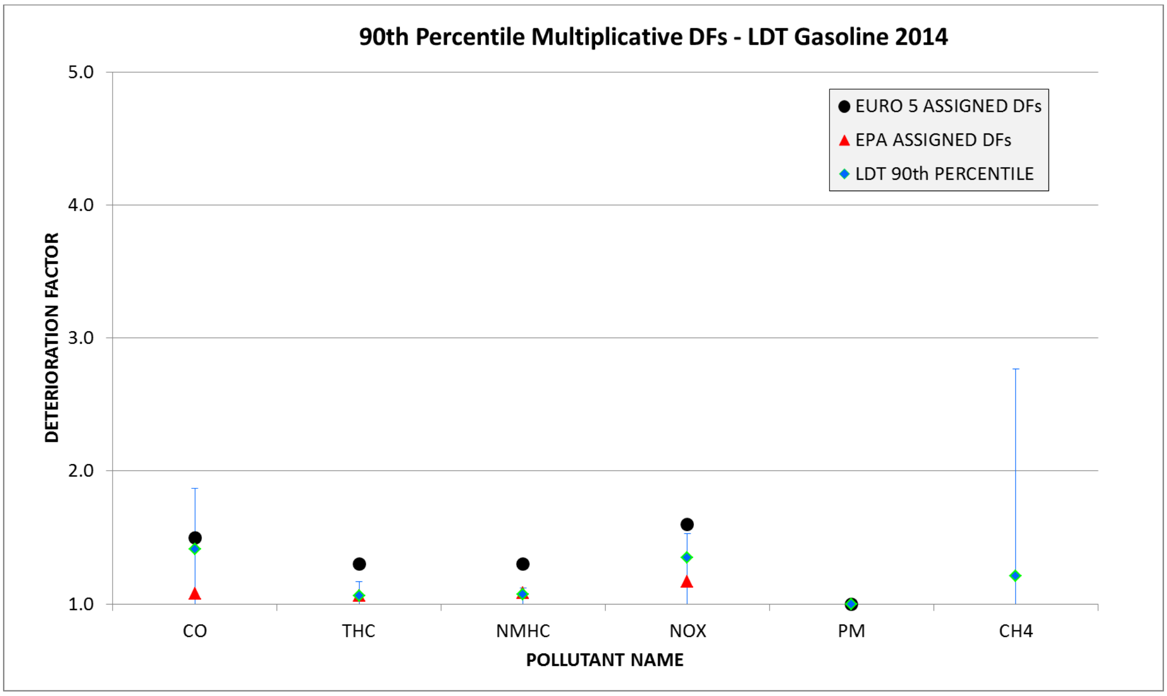


Figure A 16: Multiplicative DFs for gasoline vehicles MY 2014 at 160,000 km: 90th percentile for LDTs compared to Assigned DFs Euro 5.

European Commission
EUR 26435 EN – Joint Research Centre – Institute for Energy and Transport

Title: Durability demonstration procedures of Emission Control Devices for Euro-6 Vehicles

Author(s): Maria Cristina Galassi, Giorgio Martini

Luxembourg: Publications Office of the European Union

2014 – 60 pp. – 21.0 x 29.7 cm

EUR – Scientific and Technical Research series – ISSN 1831-9424 (online), ISSN 1018-5593 (print)

ISBN 978-92-79-35087-0 (PDF)
ISBN 978-92-79-35088-7 (print)

doi:10.2789/18532

LC-NA-26435-EN-N

JRC Mission

As the Commission's in-house science service, the Joint Research Centre's mission is to provide EU policies with independent, evidence-based scientific and technical support throughout the whole policy cycle.

Working in close cooperation with policy Directorates-General, the JRC addresses key societal challenges while stimulating innovation through developing new methods, tools and standards, and sharing its know-how with the Member States, the scientific community and international partners.

Publications Office

doi:10.2789/18532

ISBN 978-92-79-35087-0