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TNO report

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Application of Gasoline Particulate Filters, effects and possibilities

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Samenvatting

In opdracht van het Ministerie van Infrastructuur en Waterstaat heeft TNO een studie verricht naar de mogelijke toepassing van roetfilters op voertuigen die uitgerust zijn met een benzinemotor met directe brandstofinspuiting (GDI: Gasoline Direct Injection technologie). Deze roetfilters worden ook wel aangeduid als Gasoline Particulate Filters (GPF).
Sinds 1 september 2017 is de Euro 6c emissienorm van kracht die voor benzinevoertuigen met GDI een nieuwe limietwaarde voor de emissies van deeltjesaantallen (PN) heeft. Deze nieuwe limietwaarde is met een factor tien verlaagd naar 6 * 10^{11} deeltjes per kilometer. Daarnaast is er een norm van 9 * 10^{11} deeltjes per kilometer voor de RDE praktijktest geïntroduceerd.
Voor het behalen van deze nieuwe limietwaarden zijn twee opties in beeld: verbetering van de brandstofinspuiting in combinatie met optimalisatie van de verbranding of het plaatsen van een GPF. In deze studie worden beide opties onderzocht waarin in de hoofdstukken 2 t/m 5 de technische details worden gerapporteerd en deze samenvatting met name de beleidsmatige zaken belicht.

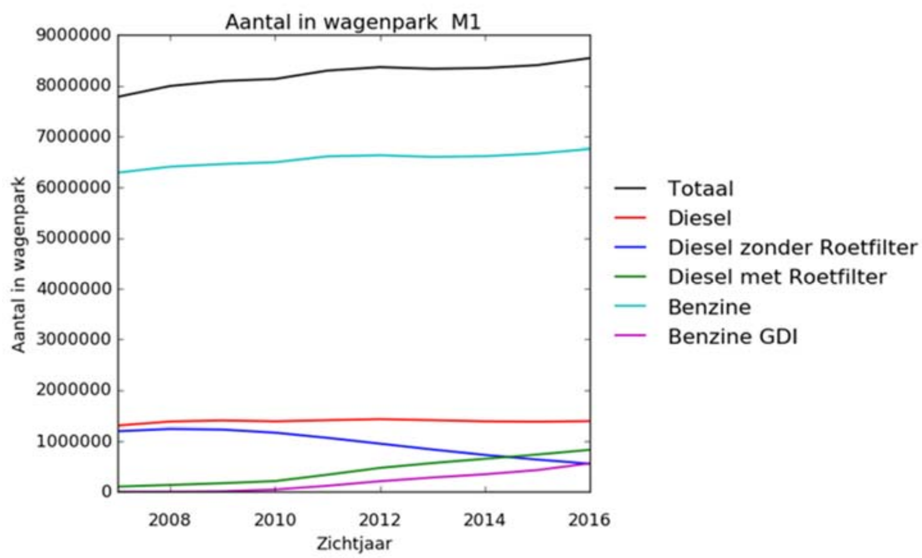
Komen er roetfilters op direct-injectie benzineauto's?
In het verleden was het beeld helder: dieselauto's zonder roetfilter stoten veel fijnstof uit en benzineauto's weinig. Zelfs de laatste generatie dieselauto's zonder roetfilter heeft veel hogere emissies dan alle andere moderne voertuigen. Inmiddels beschikt het grootste deel - meer dan 60% - van de Nederlandse dieselpersonenauto's over een roetfilter. De uitlaatgassen van dieselauto's met een goed werkend roetfilter bevatten extreem weinig fijnstof, zelfs minder dan die van de conventionele benzineauto's met indirecte benzine inspuiting. En binnen de benzineauto's vindt er een omslag plaats naar een nieuwe technologie, directe benzine inspuiting (GDI). Een GDI stoot veel minder fijnstof uit dan een dieselauto zonder filter, maar wel wat meer dan een diesel met filter. In Tabel 1 wordt een indruk gegeven van gebruikelijke emissieniveaus.

Tabel 1: Emissiefactoren voor fijnstof in de uitlaatgassen van moderne Euro-6 auto's en de laatste generatie Euro-4/Euro-5 diesels zonder roetfilter. Zowel de emissiefactoren voor deeltjesmassa als voor deeltjesaantallen zijn gegeven. De emissiefactoren zijn gepresenteerd als een bereik (range) om uit te drukken dat de emissies sterk afhankelijk (kunnen) zijn van rijomstandigheden en eventuele filterregeneraties.

	Massa fijnstof deeltjes PM (mg/km)	Orde van grootte aantal fijnstof deeltjes PN (#/km)
Dieselauto zonder roetfilter	30 – 40	≈ 10^{14}
Benzineauto met GDI	0,5 – 5	≈ 10^{12} – 10^{13}
Benzineauto met indirecte injectie	0,1 – 5	≈ 10^{11} – 10^{13}
Dieselauto met roetfilter	0,1 – 2	≈ 10^{11} – 10^{12}
Ter illustratie: fijnstof door de motor opgenomen uit de buitenlucht – ruwe schatting[1]	0,01	10^9 – 10^{10}

[1] Uitgaande van een auto met motorinhoud 1.5 liter, bij 2500 toeren en snelheid 30km/u en een fijnstof concentratie in de buitenlucht van 25 microgram/m3.

De laatste tien jaar is het percentage GDI's in de nieuwverkopen gestegen van enkele procenten naar bijna de helft van de Europese verkoop. Ook in Nederland zijn steeds meer benzineauto's uitgerust met GDI technologie, zie Figuur 1.
In het hogere segment is GDI inmiddels de dominante technologie en ook in de andere segmenten neemt de toepassing ervan toe. Het is de verwachting dat de groei in het midden- en lagere segment de komende jaren zal doorzetten, vanwege de voordelen van GDI in rijeigenschappen en een lager benzineverbruik. Met als gevolg dat over een jaar of tien het merendeel van de benzineauto's over GDI technologie zal beschikken, resulterend in een totale uitstoot van fijnstof door GDI's van 100-200 ton per jaar. GDI's worden daarmee verreweg de grootste bron van fijnstofemissies uit de uitlaat in het segment personenauto's.[2] In vergelijking met de fijnstofemissies ten gevolge van slijtage van remmen, banden en wegdek blijft de omvang overigens beperkt. De introductie van GDI technologie heeft vrijwel geen invloed op de concentraties van PM_{10} en $PM_{2,5}$ in de buitenlucht en daarmee op het halen van de Europese luchtkwaliteitsnormen voor fijnstof.



Figuur 1: GDI is een klein aandeel van het Nederlandse wagenpark van personenauto's (M_1) maar groeit snel sinds 2010. (TNO rapport 11872).

Voor benzineauto's met GDI technologie bestaan er, net als voor dieselauto's, Europese eisen aan de uitstoot van fijnstof uit de uitlaat. Dit omvat eisen aan aantallen fijnstofdeeltjes als ook aan de totale massa van de deeltjes, zie Tabel 2. Voor benzineauto's met indirecte injectie zijn er geen fijnstof eisen.
Per 1 september 2017 zijn de normen voor benzineauto's met GDI aangescherpt. De nieuwe RDE-eis wordt gezien als de meest strenge, omdat deze niet alleen in relatief gunstige laboratorium omstandigheden gehaald moet worden, maar ook onder sterk uiteenlopende omstandigheden gemeten op de weg. De combinatie van een agressievere rijstijl, koude buitenlucht en brandstof van lage kwaliteit wordt gezien als de meest kritische test voor de deeltjeseis van GDI's.

[2] Daarbij is uitgegaan van GDI's zonder roetfilter, rekening houdend met de aanscherping van de emissie-eis voor GDI per 1 september 2017 en de huidige jaarkilometrages van benzine- en dieselauto's. Tevens is verondersteld dat roetfilters op dieselauto's over de hele levensduur van de auto goed blijven werken.

Tabel 2: Europese fijnstof normen voor nieuwe benzineauto's met GDI technologie.[3]

		PM (mg/km)	PN (#/km)
Euro-6 (laboratorium test)	Tot 1 sept 2017 Per 1 sept 2017 voor nieuwe typegoedkeuringen en per 1 sept 2018 voor alle registraties	4,5 4,5	6×10^{12} 6×10^{11}
RDE (praktijk test)	Per 1 sept 2017 voor nieuwe typegoedkeuringen en per 1 sept 2018 voor alle registraties	-	9×10^{11}

Het is niet de verwachting dat de aangescherpte eisen zullen leiden tot minder GDI technologie of verschuiving van benzine naar diesel. Daarvoor zijn de kosten om met GDI aan de normen te voldoen te laag en de voordelen van GDI (in brandstofverbruik en rijeigenschappen) te groot.

De Euro-6 norm die gold tot 1 september 2017 kon door een GDI worden gehaald, zonder dat toepassing van een roetfilter – GPF, Gasoline Particulate Filter – nodig was. Aanpassingen in de motorafstelling bleken daartoe voldoende te zijn.
De nieuwe normen per 1 september 2017 schrijven niet het gebruik voor van roetfilters op GDI's. Het staat de autofabrikanten vrij om de technologie te kiezen, zolang ze aan de normen voldoen. Mercedes en het VW-concern hebben direct bij de introductie van de Euro-6 norm aangekondigd GPF's te gaan toepassen. Peugeot is gestart met de levering van een benzinemotor met GPF in het middensegment. Diverse fabrikanten zijn onder Euro-6 nog enige tijd door gegaan met de levering van GDI's zonder GPF en haalden de normen met verdere optimalisatie van de motorafstelling en verbetering van de benzine-injectie.
Ten gevolge van de introductie van de RDE norm is de situatie in de loop van 2018 omgeslagen. Sinds die tijd zijn geen introducties van nieuwe GDI benzineauto's zonder GPF waargenomen. Alle GDI voertuigen die aan de RDE eisen voldoen hebben tot dusverre een GPF. De levensduureisen en de bijzondere omstandigheden die kunnen optreden in praktijktests uitgevoerd door onafhankelijke partijen, alsook de nog niet beschikbare verbeterde GDI technologie zijn de belangrijkste redenen om GPF's toe te passen.

De GPF is een goedkope en beschikbare technologie. De GPF kan worden geïntegreerd in de behuizing van de bestaande uitlaatgasnabehandeling, zoals de driewegkatalysator, zodat er geen aanpassingen aan het voertuigontwerp zijn vereist. Inbouw kan met minimale of zelfs zonder aanpassing van de motorinstellingen. De hoge mate van integratie biedt autofabrikanten de ruimte om een besluit over het wel of niet toepassen van een GPF tot het laatste moment uit te stellen.

[3] Fabrikanten krijgen nog 1 (Euro 6, WLTP en RDE-PN-eis) om bestaande modellen aan te passen aan de aangescherpte normen.

Ze kunnen zelfs besluiten om op een voorserie GPF toe te passen en dat later weer terug te draaien. Er wordt melding gemaakt van een meerprijs voor een GPF in de orde van vijftig euro. Bij grootschalige toepassing zou de meerprijs voor autofabrikanten substantieel lager kunnen liggen.

Toepassing van een GPF of vergaande optimalisatie van de motor (afstelling en brandstofinjectie) zijn de enige twee opties om aan de fijnstof emissienormen voor GDI's te voldoen. Van betere kwaliteit motorolie of speciale benzine mag in de praktijk een beperkte reductie van de uitstoot worden verwacht[4], maar zelfs als een autofabrikant deze betere motorolie en benzine aanbeveelt, wordt er geen rekening mee gehouden bij de toetsing of een GDI aan de normen voldoet, omdat er geen garantie is dat zulke aanbevelingen worden opgevolgd[5].

Vanuit milieuoogpunt heeft toepassing van een GPF duidelijk voordelen ten opzichte van vergaande optimalisatie van de motor:

- Met een GPF is een sterkere reductie van de fijnstof uitstoot haalbaar. Het gemiddeld afvangpercentage van een GPF ligt nu rond de 85% en een GPF werkt niet alleen goed voor deeltjes die onder de normstelling vallen (deeltjes groter dan 23 nm), maar even goed voor ultrafijne deeltjes met een grootte tussen 10 en 23 nm. In principe zijn verschillende afvangpercentages mogelijk, maar 85% is voldoende om de normen te halen, zonder dat nadelige effecten, zoals een toename in het brandstofverbruik, optreden.
- Een GPF wordt gezien als een robuuste oplossing. Een GPF werkt onder alle rijomstandigheden vergelijkbaar. Een GPF is in staat effecten van variaties in rijgedrag, omgevingscondities en brandstofkwaliteit en slijtage of vervuiling van de motor (bijvoorbeeld door olieverbruik) deels op te vangen. De ervaring heeft geleerd dat motoroptimalisatie daarentegen juist gevoelig is voor rijomstandigheden en omgevingscondities en kan leiden tot hoge praktijkemissies. De levensduur van een GPF is naar verwachting langer dan van een roetfilter op een dieselauto, omdat een GPF geen actieve regeneratie (schoonbranden van het filter) nodig heeft. Doordat er as in de GPF achterblijft lijkt de filtratie efficiëntie toe te nemen met leeftijd. Goed onderhoud van het GPF en regelmatige controle of het niet is verwijderd blijft vereist.[6]
- Een GPF zal waarschijnlijk het brandstofverbruik zeer beperkt verhogen, maar dat is wellicht ook het geval als door motoroptimalisatie de PN eis gerealiseerd moet worden.

Op dit moment is de toepassing van de GPF op nieuwe GDI's gemeengoed. Door de hoge mate van integratie in bestaande behuizingen en de geringe aanpassingen aan de motorinstelling, zouden autofabrikanten eenvoudig weer kunnen afstappen van toepassing van GPF's, als het halen van de normen met motorafstelling en betere brandstofinjectie mogelijk blijkt.

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[4] De mate van emissiereductie door betere benzine- of oliekwaliteit hangt sterk af van het motorconcept en zodoende zal het effect per fabrikant en zelfs per motortype verschillen.

[5] Er zijn geen initiatieven bekend om de Europese benzine- en oliekwaliteitseisen zover aan te scherpen dat een beperking van de fijnstof uitstoot mag worden verwacht.

[6] Indien een GPF wordt verwijderd, zal dat in veel gevallen ook resulteren in een sterk verhoogde NOx, CO en HC emissie, omdat GPF en 3-weg katalysator waarschijnlijk gecombineerd zijn op één substraat of in één behuizing.

De onderstaande maatregelen zouden kunnen waarborgen dat de fabrikanten ook op langere termijn op grote schaal voor de meer robuuste en gewenste GPF technologie blijven kiezen. Daardoor zullen de kosten verder kunnen dalen.

- Nieuwe strengere Europese normen
  Over nieuwe normen, vaak aangeduid als Euro-7[7], wordt inmiddels verkennend gesproken. Euro-7 biedt aanknopingspunten om de toepassing van GPF's zeker te stellen. Over de inwerkingtreding van eventuele nieuwe normen gaat een periode van minimaal 5 jaar[8] heen. De Europese wetgeving biedt weinig ruimte om de toepassing van een GPF via nationale regelgeving te verplichten.

- Onafhankelijke toetsing in Europese RDE wetgeving
  Het 4e RDE pakket, dat in 2018 is vastgesteld, bevat de mogelijkheid dat derde partijen kunnen controleren of een personenauto aan de emissienormen voldoet.
  Als auto's regelmatig gecontroleerd worden onder een breed bereik van praktijkomstandigheden (zoals omgevingscondities, rijgedrag en kilometerstand), dan zullen de fabrikanten naar verwachting voor de meest robuuste technologie kiezen om minder risico's te lopen.

- Verlagen onzekerheidsmarge in Europese RDE wetgeving
  Nieuwe GDI's moeten in het laboratorium voldoen aan een eis van 6×10^{11} deeltjes per km en in RDE-tests op de weg aan 9×10^{11}. Het verschil tussen beide eisen is een onzekerheidsfactor van 1,5 die in RDE is geïntroduceerd om onder meer rekening te houden met meetonnauwkeurigheden en de grote spreiding in deeltjesaantallen bij opeenvolgende testen van hetzelfde voertuig. Fabrikanten zullen daar deels rekening mee houden in de ontwikkeling van de technologie. Mogelijk zal met één test geen uitsluitsel te geven zijn over de gemiddelde deeltjes uitstoot van een voertuig.
  De factor 1,5 wordt regelmatig geëvalueerd, omdat er inmiddels betere meetapparatuur beschikbaar is.

  Een eventuele verlaging van de onzekerheidsmarge zou in principe relatief snel te regelen zijn, maar de stap zal mogelijk onvoldoende groot zijn[9] om het verschil te maken. Tevens mag worden verwacht dat veel partijen zullen aandringen op een langere *leadtime*, omdat ze recent meetapparatuur hebben aangeschaft. De ontwikkeling van PEMS meetapparatuur is zeer snel gegaan, de eerste prototypes waren pas beschikbaar in het najaar van 2015. De verwachting is dat deze ontwikkeling verder doorzet.

[7] Euro-7 wordt naar verwachting een set brandstof-neutrale eisen (zelfde limietwaarden voor diesel- en benzineauto's). Voor dieselauto's is er echter geen aanleiding om de fijnstof normen aan te scherpen, omdat de normen voldoende zijn om een effectief roetfilter toe te passen. Het is de vraag of de brandstof-neutrale fijnstof eisen dan zover worden aangescherpt dat voor GDI benzineauto's de facto een GPF nodig is. De Europese Commissie wil in de 1e helft van 2019 een oriënterend onderzoek naar Euro-7 starten.

[8] Voor onderhandelingen en overgangstermijn voor autofabrikanten.

[9] De onzekerheidsmarge in RDE voor de NO_x eis voor dieselauto's is inmiddels verlaagd van 1,5 naar 1,43. Dit geeft een indicatie van de waarschijnlijke omvang van eventuele aanpassingen.

- Strengere levensduur eisen
  Robuuste technologie, zoals GPF, is voor fabrikanten een veilige optie als de fabrikanten meer verantwoordelijk worden voor de emissies van het voertuig over de hele levensduur. Als onderdeel van de lopende ontwikkeling van het 4e RDE-pakket worden de eisen uitgewerkt voor de controle van de duurzaamheid van emissiereductie technologie in *in-service-conformity* programma's. De duurzaamheid wordt echter alleen gecontroleerd voor goed onderhouden auto's tot een kilometrage van 100.000 km. Een uitbreiding van de controle van de duurzaamheid naar bijvoorbeeld 160.000 km[10], vergroot de waarschijnlijkheid, dat fabrikanten vasthouden aan de veilige optie van een GPF. Aanpassing van de duurzaamheidseis zal worden overwogen als onderdeel van toekomstige Euro-7 normen.

- Verlagen afkapgrens deeltjesgrootte
  Momenteel worden alleen vaste deeltjes groter dan 23 nm meegeteld voor het halen van de fijnstof normen. Door deze afkapgrens blijft 20-50% van het totale aantal deeltjes in uitlaatgassen buiten beschouwing. De afkapgrens is gebaseerd op de reproduceerbaarheid van de metingen toen de procedures voor het meten van deeltjesaantallen zijn ontwikkeld. De toenmalige beperkingen gelden niet meer en er wordt dan ook gewerkt aan procedures om de afkapgrens te verlagen naar 10 nm of mogelijk zelfs 7 nm. Aanpassing van de afkapgrens zal worden overwogen als onderdeel van toekomstige Euro-7 normen.
  Het is de moeite waard om deze route in ieder geval te bewandelen. Als de afkapgrens wordt verlaagd naar 7 nm of 10 nm en de normen niet worden verhoogd, dan lijkt toepassing van een GPF zonder meer vereist.

- Nationale stimulering
  In het verleden zijn roetfilters op dieselauto's in Nederland succesvol gestimuleerd met fiscaal beleid, op basis van en vooruitlopend op de Europese normen voor fijnstof van 5 mg/km. Hierdoor liep de snelheid van introductie in Nederland twee jaar voor op die in de rest van Europa. Zolang alle nieuwe GDI benzineauto's met roetfilters zijn uitgerust, is er geen nationale stimulering van GPF's nodig.
  Mocht er in de toekomst toch aanleiding zijn om de toepassing van GPF's te stimuleren, dan is het voor de hand liggend om de "stimulering" vorm te geven als een fiscale toeslag op direct-injectie benzineauto's zonder GPF.

  Een nationale stimuleringsregeling kan alleen werken als de registratie van de waarden van fijnstof deeltjesaantallen op orde is. Geconstateerde onvolkomenheden in het kentekenregister waren aanleiding om Europese afspraken over de registratie aan te scherpen. De komende periode zal moeten blijken of deze afspraken effectief zijn.

  De norm voor de nationale stimuleringsregeling dient zodanig streng te zijn dat een direct-injectie benzineauto met een GPF er wel voor in aanmerking komt en één zonder GPF niet. Op dit moment valt niet vast te stellen waar de grens ligt tussen emissies van GDI's met of zonder GPF.

[10] Bij typegoedkeuring wordt aan emissiereductietechnologie een duurzaamheidseis van 160.000 km gesteld.

Vrijwel alle geregistreerde GDI's met GPF zijn emissiewaarden geregistreerd die gelijk zijn aan de limietwaarden voor Euro-6 (6×10^{11} deeltjes per km) en RDE (9×10^{11} deeltjes per km).

Europese regels[11] bieden in ieder geval ruimte voor de introductie van een nationale stimuleringsregeling, zolang deze gebaseerd is op een toekomstige Europese norm, technologie neutraal is en de hoogte van de stimulering in lijn is met de meerkosten.

Conclusie

De nieuwe Euro-6 en RDE normen voor de uitstoot van fijnstof door direct-injectie benzineauto's hebben ertoe geleid dat GPF roetfilters standaard worden toegepast. Een GPF is een goedkope en robuuste manier om de uitstoot van fijnstof te reduceren. Mochten autofabrikanten alsnog besluiten om geen GPF te kiezen, dan bieden de toekomstige Euro-7 normen, waarover momenteel verkennend wordt gesproken en/of nationale fiscale stimulering van GPF's bij direct-injectie benzineauto's mogelijkheden om de toepassing van GPF's te waarborgen. Voordat een nationale stimulering wordt geïntroduceerd verdient het aanbeveling nader te onderzoeken hoe streng de norm moet worden, of een voldoende hoge stimulering kan worden verstrekt en of de registratie van de waarden van fijnstof deeltjesaantallen verbeterd is.

[11] De Europese Commissie heeft richtsnoeren gepubliceerd voor financiële stimulering van voertuigen die voldoen aan een toekomstige Europese norm. Zo'n norm die tot toepassing van GPFs moet leiden is er (nog) niet.
http://ec.europa.eu/transparency/regdoc/?fuseaction=list&coteId=2&year=2009&number=1589&version=ALL&language=en

Summary

Commissioned by the Ministry of Infrastructure and Water Management,
TNO has carried out this study into the possible application of Gasoline Particulate Filters (GPF) on vehicles equipped with a petrol engine with direct fuel injection (GDI: Gasoline Direct Injection technology). As from 1 September 2017 the Euro 6c emissions standard came into force introducing a new limit value for the emissions of particle numbers (PN) of new petrol passenger cars. The limit value is reduced by a factor of ten to 6 * 10^{11} particles per kilometre. Additionally the RDE standard of 9 * 10^{11} came into force. To achieve these new limit values two technological options are available: improvement of fuel injection combined with combustion optimization or application of a GPF. Both options are examined in this study in which in the chapters 2 through 5 the technical details are reported. This summary deals in particular with policy matters.

Will Gasoline Particulate Filters be installed on new direct injection petrol cars?
In the past, the vehicle emissions landscape was as clear as simple: high particulate matter emissions related to diesel cars without a particle filter (DPF) and very low emissions of petrol cars. Even the latest generation of diesel cars without DPF has much higher emissions than all other modern vehicles. Nowadays the largest share, more than 60% of the Dutch diesel passenger cars, is equipped with a DPF and if the DPF is properly functioning particulate matter emissions are very low, even below the level of emissions of conventional petrol cars with indirect petrol injection. Within the petrol cars segment there is a shift to a new technology, Gasoline Direct Injection (GDI). Though at least one order of magnitude below the emissions of diesel cars without a filter, GDIs emit slightly more particulate matter and particles than diesel cars with a DPF. In Table 1 an impression is given of usual emission levels.

Table 1: Emission factors for particulate matter and particles in the exhaust gases of modern Euro-6 cars and the latest generation of Euro 4/Euro 5 diesels without a DPF. Both the emission factors for particulate mass as for particle numbers are given. The emission factors are presented as a range (range), in order to express that the emissions strongly depend on driving conditions and filter regenerations.

	Order of magnitude PM (mg/km)	Order of magnitude PN (#/km)
Diesel without DPF	30 - 40	≈ 10^{14}
GDI (direct fuel injection)	0,5 - 5	≈ 10^{12} – 10^{13}
PFI (indirect fuel injection)	0,1 - 5	≈ 10^{11} – 10^{13}
Diesel with DPF	0,1 - 2	≈ 10^{11} – 10^{12}
For the purpose of illustration only: typical particles intake by the engine from ambient air – rough estimate[1]	0,01	10^{9} – 10^{10}

[1] Based on a vehicle with an engine swept volume of 1.5 litre at 2500 rpm and 30km/h vehicle speed and ambient air particulate matter concentration of 25 microgram/m^3.

Over the last 10 years GDI share in new vehicle sales increased from a few percent to almost half of the European petrol car sales. In The Netherlands, more and more petrol cars are equipped with GDI technology, see Figure 1. By now GDI is the dominant technology in the upper segment, and its application in the other segments is increasing. It is expected that the growth in the mid and lower segment will continue over the next few years, because of the advantages of GDI in driving characteristics and lower fuel consumption. As a result in a decade from now the majority of petrol cars will have GDI technology. GDIs will become the largest contributor to the overall particulate matter exhaust gas emissions of the passenger cars segment, with total emissions of 100-200 tons per year.[2] In comparison to the particle emissions linked to wear and tear of brakes, tires and road surfaces the contribution of GDI exhaust emissions remains very limited. The introduction of GDI technology has virtually no impact on the concentrations of PM_{10} and $PM_{2,5}$ in the ambient air and thus has no impact on achieving the air quality standards for fine particles.

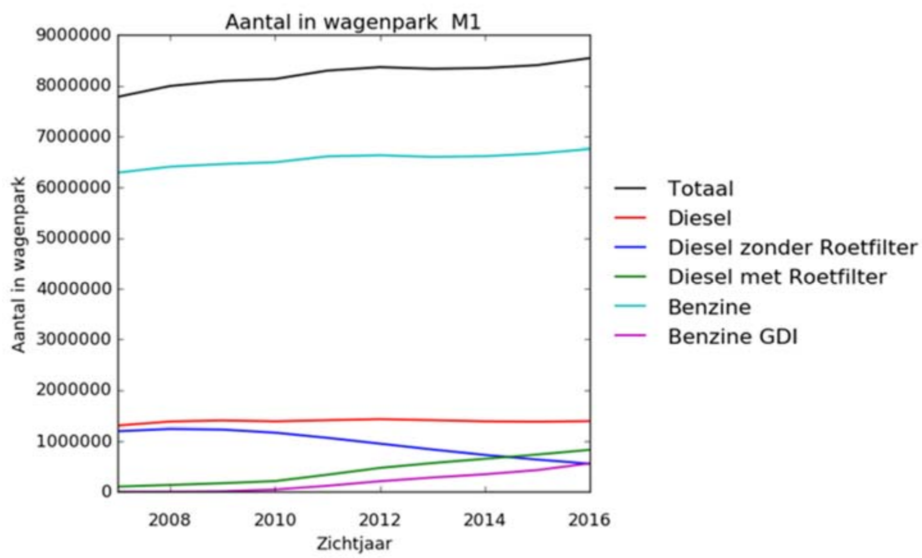

Figure 1: GDI (purple line Benzine GDI) is a small share of the Dutch fleet of passenger cars (M1, black line) but is growing rapidly since 2010. (TNO report 2016 11872).

For petrol cars with GDI technology, as well as for diesel cars, exhaust gas emissions are bound by European limit values for both numbers of fine particles as well as total mass of particulate matter, see Table 2. For conventional petrol cars with indirect injection there are no such requirements. As from 1 September 2017 the standards for petrol cars with GDI have been tightened. The new RDE requirements are considered to be the most stringent, because the limit value has to be met not only in relatively favourable laboratory conditions, but also under a wide range of on-road driving conditions. In particular an on-road test performed at low temperatures, with an aggressive driving style and fuel quality at the boundaries of the allowed specifications, is considered to be very demanding to meet the RDE PN limit for GDIs.

[2] In a scenario with no GPF application, taking account of the September 2017 limit values and based on constant mileages. The assumption is made that both DPF and GPF will be functioning properly throughout the vehicles lifetime.

Table 2: European particulate matter and particle number standards for new petrol cars with GDI technology.[3]

		PM (mg/km)	PN (#/km)
Euro-6 (laboratory test)	Untill 1 September 2017	4,5	6×10^{12}
	As from 1 Sept 2017 for new type approvals and as of 1 Sept 2018 for all new registrations	4,5	6×10^{11}
RDE (on-road test)	As from 1 Sept 2017 for new type approvals and as of 1 Sept 2018 for all new registrations	-	9×10^{11}

It is unlikely that the new more stringent requirements will impact the trend towards an increase of GDI technology or might cause a shift from petrol to diesel. The costs of GDI technology meeting the standards are very limited and the benefits of GDI (in terms of fuel economy and drive-ability) are too large.

The previous standards could be met with a GDI, without requiring the application of a particulate filter – GPF, Gasoline Particulate Filter. Adjustments in engine settings were found to be sufficient for this purpose. The new standards from 1 September 2017 will not prescribe application of GPFs on GDIs. Car manufacturers can those any technology as long as the standards are met. Mercedes and VW Group have announced the introduction of GPFs on their new vehicles per Euro-6. Peugeot is actually delivering mid-range vehicles with GPF. Various manufacturers continued delivering GDI without GPF under the Euro-6 (laboratory) standard, but with further optimization of the engine settings and improvements of the gasoline-injection.
As a result of the upcoming RDE standards the situation changed in the course of 2018. No new GDI introduction have been observed without GPF being applied.
So far all GDIs meeting the RDE requirements are equipped with a GPF.
The durability and special circumstances that may occur in the on-road tests carried out by independent parties as well as the not yet available improved GDI technology, are the main reasons for application of GPFs.

The GPF is a relatively cheap and readily available technology. The GPF will be integrated in the housing of the existing exhaust gas aftertreatment, such as the three-way catalytic converter, so that no modifications to the vehicle design are required. And only minimal or even no adjustments of the engine settings are required. The high level of integration provides car manufacturers the possibility to postpone a decision whether or not to apply a GPF to the very last moment. They may even decide to apply GPFs on a first series of vehicles and to remove the GPF from the final production series. Additional costs of GPF application are reported to be in the order of 50 euros and may even be substantially lower in large-scale application.

Only two options are available to meet the particulate matter emission standards for GDIs: either GPF application or far-reaching optimization of the engine (adjustment settings and fuel injection system).

[3] Manufacturers get even 1 (Euro 6) up to 2 years (RDE) to existing models to adapt to the tighter standards.

A limited reduction of fine particle emissions can be expected if higher quality motor oil or petrol fuel is used[4], but even if a car manufacturer recommends a higher quality of oil and fuel, the effect is not taken into account in the assessment whether a GDI fulfils the standards, because there is no guarantee that the recommendations are followed[5].

From an environmental point of view application of a GPF has clear advantages over far-reaching optimization of the engine:

- A GPF allows for stronger reductions of fine particle emissions. The average filtration rate of a GPF is around 85% and a GPF is effective in reducing emissions of particles of all sizes, ranging from particles greater than 23 nm that are measured under the protocols of current European legislation, to ultra-fine particles with a size between 10 and 23 nm. The filtration rate strongly depends on the lay-out of the GPF, but an 85% rate is considered to strike a balance between the emissions reductions required and the avoidance of adverse effects, such as an increase in fuel consumption.
- A GPF is considered to be a robust solution. It operates similarly under all driving conditions. A GPF will absorb changes in engine out particle emissions due to variations in driving behaviour, ambient conditions (temperature) and fuel specification, but also due to wear (high oil consumption) and fouling of the engine. On the other hand experience shows that engine optimization is generally sensitive to driving and ambient conditions and can lead to high real world emissions. The life span of a GPF is expected to be longer than of a DPF on a diesel car, because a GPF has no active regeneration (clean burning of the filter). Over the duration of its life, the GPF is expected to become more effective with the ash accumulation. Nevertheless regular maintenance and inspections if the GPF is not removed is vital to good operation of the GPF over the lifetime of the vehicle.[6]
- The GPF itself may cause a very limited increase of fuel consumption, but engine optimization goes at the expense of fuel economy as well.

At the moment GPF is the dominantly applied technology on new GDIs. The high level of integration in the housing of the existing exhaust gas aftertreatment systems and the minimal or even no adjustments of the engine settings required, allow manufacturers to drop GPF application at any time if meeting the standards with engine optimization or improve fuel injection turns out to be possible.

The measures below could ensure continued large-scale application of the robust and environmentally preferred GPF technology. The connected cost reductions would ensure the application of the GPF for years to come.

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[4] The extent of emission reduction by better fuel or motor oil quality depends on the engine concept and will strongly vary from one manufacturer and even one engine type to another.
[5] There are no initiatives known to improve the European fuel and motor oil quality standards to an extent that an impact on fine particle emissions can be expected.
[6] Due to the strong integration of the GPF with other elements of the emission after-treatment system, e.g. the 3-way catalyst, removal of the GPF will generally also result in a steep rise of NOx, CO and HC emissions.

- New more stringent European standards
  First exploratory discussion on new standards, often referred to as Euro-7[7]. Euro-7 will offer an opportunity to ensure GPF application. The coming into force of new standards will take at least another 5 years[8]. The current European legislation offers The Netherlands very limited room for national mandatory introduction of GPFs.

- Independent RDE testing
  The 4th RDE package, that has been decided upon in 2018 allows third parties to check if vehicles fulfil the RDE emissions standards. If cars are systematically checked under a wide range of real world conditions such as ambient conditions, driving behaviour and odometer reading, manufacturers will be stimulated to apply the robust GPF technology in order to avoid risks of non-compliance.

- Reduce uncertainty margin in European RDE-legislation
  New GDI models will have to comply with the requirement of 6×10^{11} particles per km in the laboratory test and 9×10^{11} in RDE tests on the road. The difference between the two requirements referred to above, an uncertainty margin of 1.5, is introduced in RDE, inter alia, to take account of measurement inaccuracies and the observed spread in measurement results between different tests with the same vehicle. Given this spread manufacturer will likely develop and apply technology delivering emissions substantially below the RDE standards.
  The margin of 1.5 will be reviewed regularly, because better measurement equipment comes available. A reduction of the margin could be implemented relatively quickly but may be insufficient[9] to encourage manufacturers to make the U-turn to GPFs. Also it is to be expected that many parties will insist on a longer lead time, because they recently have purchased measuring equipment. PEMS measurement equipment evolved very quickly over the last few years, given the first prototype were only available in the autumn of 2015. Further improvements are expected.

- Stricter durability requirements
  For manufacturers the application of robust technology, such as GPF, is a safe option if they become more responsible for the emissions over the full service life of the vehicle. As part of the 4th RDE package requirements will be developed to check the durability of emission control technology in in-service-conformity programs. Durability will only be checked for well-maintained cars up to a mileage of 100,000 km.

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[7] Euro-7 is expected to be a set of fuel-neutral requirements (same limit values for diesel and petrol cars). For diesel vehicles, however, there is no reason to strengthen the standards for fine particles, as effective particulate filter are already ensured by the current standards. In the perspective of fuel-neutral standards the justification to strengthen fine particle limit values just for the segment of GDI petrol in order to ensure GPF application might not be convincingly.
The European Commission announced that a first Euro-7 study will start in the 2nd half of 2018.

[8] For negotiations and lead time for car manufacturers

[9] Recently the uncertainty margin for RDE NO_x has been reduced from 1,5 to 1,43, being an indication of the magnitude of reduction that may be expected.

An extension of the emissions durability period to, for example, 160,000 km[10], increases the probability, that manufacturers will continue to apply GPFs. Extension of the durability period will be considered as part of Euro-7 developments.

- Lower cut-off threshold particle size
  Currently, only solid particles larger than 23 nm are measured under the protocols of the particulate matter standards. Due to this cut-off threshold 20-50% of the total number of particles in exhaust gases are not measured. The selection of the cut-off threshold is based on the reproducibility of the measurements when the procedures for measuring particle numbers were developed. The restrictions are no longer necessary and developments are ongoing to reduce the cut-off threshold to 10 nm or possibly even 7 nm. Lowering the cut-off threshold will be considered as part of Euro-7 developments. It is worth proceeding with this route. Lowering the cut-off threshold to 7 or 10 nm while not increasing the PN limit values, is expected to ensure GPF application.

- National incentives
  In the past, particulate filters on diesel cars in The Netherlands were successfully stimulated with fiscal measures in advance of the entry into force of the European 5 mg/km particulate matter standard. Consequently the speed of introduction in The Netherlands was two years ahead of that in the rest of Europe. As long as all new GDI cars are equipped with a GPF there's no need to introduce a national incentive for GPFs. If in the future a GPF incentive becomes relevant in order to prevent for backsliding, the preferred option is to introduce a fiscal surcharge on GDIs without an GPF.

  A national incentive can only work if the registration of the values of particle numbers emissions are in order. Identified imperfections in the registries were reason for European agreements on the tightening of registration. The coming years will have to proof if the agreements were effective.

  A national surcharge requires the introduction of limit values for particle numbers and particulate matter emissions that can only be met by GDIs equipped with a GPF and not by a GDI without GPF. At the moment no clear limit values can be established that would distinguish between emissions of GDIs with and without GPF. Almost all GDIs registered so far have a registered emission value equal to the new Euro-6 (6×10^{11} particles per km) and new RDE limits ($9 X 10^{11}$ particles per km).

  European[11] rules allow anyway for the introduction of a national GPF-incentive arrangement, as long as it is based on future European standards, it is technology neutral and the level of incentive is in line with the additional cost.

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[10] Type-approval shall be to emission reduction technology at a durability requirement of 160,000 km.

[11] The European Commission has published a guidance paper for financial incentives for vehicles which comply with a future European standard. There is no such standard (yet) that de facto ensures GPF application.

Conclusion

The new Euro-6 and RDE standards for emissions of particulate matter for direct-injection petrol cars have led to the application of GPFs. GPFs are a cheap and robust way to reduce emissions of particulate matter as well as particle numbers. If car manufacturers yet decide to drop the GPF technology new Euro-7 standards, that are now being discussed exploratory, or national financial incentives offer an opportunity to ensure GPF application on direct-injection petrol cars.Before a national incentive program is introduced, it is recommended to further investigate the level of the limit values to be set, the possibilities of a sufficiently high incentive and to confirm the registration of particles numbers values have been improved.

Contents

1 Introduction

1.1 Backgrounds

At September 1st, 2017 the type approval PN limit value of petrol light-duty vehicles has been reduced from $6.0*10^{12}$ to $6.0*10^{11}$ #/km. Since September 1st, 2011 this limit value is already applicable for diesel vehicles.
In addition to this chassis dynamometer test the legislation prescribes an on-road test or Real Driving Emission (RDE) test in which the PN emission must be determined. A conformity factor (CF) of 1.0 with an uncertainty margin of 0.5 will be applied which results in a NTE (Not To Exceed) PN limit value of $9.0 * 10^{11}$ #/km. This NTE-value will be applicable for new vehicle types on September 1st, 2017 and for all new registered vehicles one year later.

In order to fulfill the current PM and PN type approval limit values LD diesel vehicles are already equipped with a diesel particulate filter (DPF), for Euro-5 in 2009, which are normally extremely effective (filtration efficiency is > 99%). When the limit values were established it was unclear if all vehicle manufacturers would install GPFs on Euro 6 GDI vehicles. Volkswagen[23] and Mercedes[24] were the first to announce a gradual application of GPFs on all European petrol vehicles.

There is a risk manufacturers will develop alternative solutions [2] and will not equip their GDI vehicles with a GPF. Consequently citizens are exposed to more particulate emissions which result in higher health costs and more premature deaths from air pollution. The costs for application of GPFs on vehicles are expected to be € 50 – € 100 and it is expected that these costs are far lower than health gains.

Furthermore emission control technologies have to comply over 160,000 km with the type approval emission limit values. Currently no balanced view on deterioration of PM emissions of GDI vehicles exists.

1.2 Objective and approach

This study is meant to obtain a better view on the advantages and needs of GPFs in petrol vehicles and to investigate the possibility to enforce the implementation of GPFs via international regulations.

1.3 Structure of this report

In this report the effects and possibilities of GPFs in GDI vehicles are investigated. The emission behaviour of GDI engines are described in Chapter 2. In Chapters 3 a detailed assessment of implementation of GPFs and emission reductions is carried out. In Chapter 4 the results are discussed. Conclusions and recommendations are given in Chapters 5 and 6.

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[23] VW Press release ce39a318-6013-4e08-a606-2165d116579b
[24] 2017-03-18, https://www.daimler.com/innovation/specials/engineoffensive.html

2 PM and PN emissions of GDI vehicles

2.1 Developments in market shares

More and more petrol vehicles have been equipped with GDI engines. In Figure 2 the European market share (per manufacturer) of petrol vehicles with direct injection (in % of petrol vehicles sold) is shown. Most manufacturers implement the GDI technology in their vehicles and the average share still increases. In 2014 34% of all new sold petrol vehicles are equipped with a GDI engine.

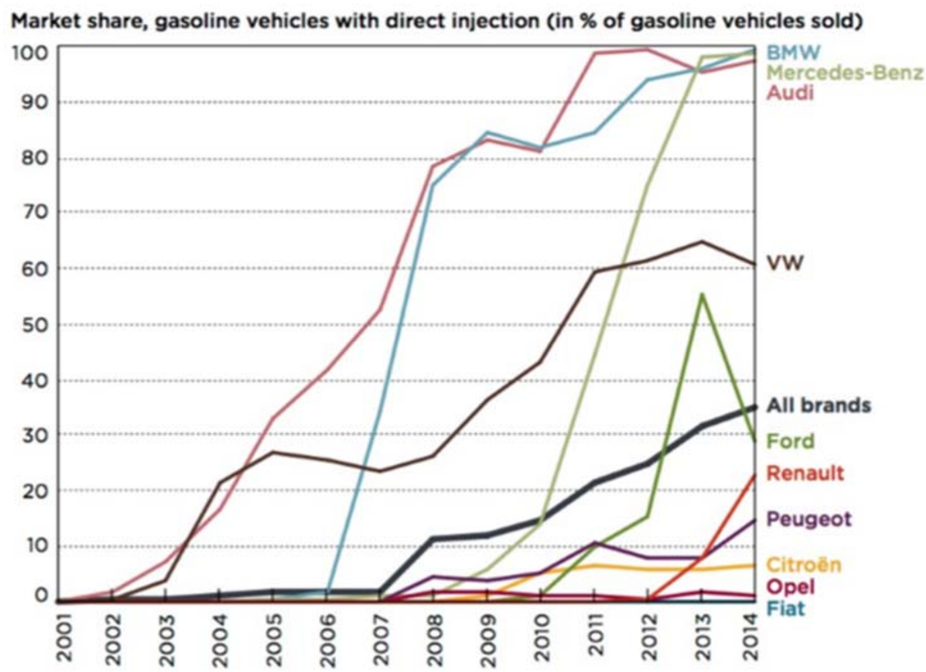


Figure 2: European market share of petrol vehicles with direct injection (in % of petrol vehicles sold per brand), source ICCT.

In Figure 3 the GDI market share per country is shown. In last decade the average GDI market share of all countries increases.

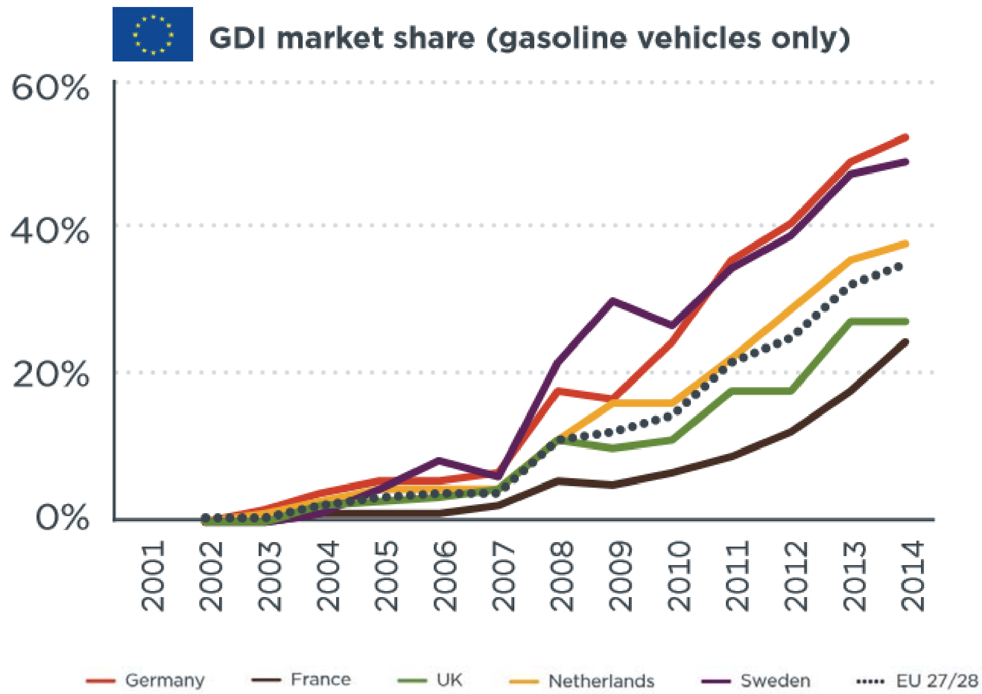


Figure 3: GDI market share (petrol vehicles only), source ICCT.

2.2 Relative contribution of PM emissions to air pollution

The fraction of GDI vehicles increases rapidly as almost halve of the sales of new petrol cars have direct injection technology. Consequently, in 10 years, in 2027, the majority of all petrol cars are GDI, from 8% of the vehicles in 2016.
In the Netherlands the ratio of petrol cars to diesel cars is six to one. Therefore, despite the larger annual mileages of diesel cars, about 75% of all the passenger cars on urban roads, and 60% on the motorway, are petrol cars.

Hence, given the large group of petrol passenger cars, responsible for about 65×10^9 km per year, emissions of these vehicles form a substantial part of the total traffic emissions in the Netherlands. The emissions of 5 mg/km particulates matter translates into 325 ton of particulates matter. It is expected that the particulates mass (PM) emission limit of 4.5 mg/km is no longer the strictest standard, but the particulates number (PN) emissions are setting the technology demand on GDI. Consequently, the total real-world particulates emissions from GDIs are expected to be in the order of 100-200 ton per year, in the foreseeable future. However, if diesel vehicles will retain the same quality of DPF, GDIs will be by far the greatest source of particulates mass emissions. Currently, in 2017, older diesel vehicles without a filter, despite their low fraction of the total fleet are still dominant in the particulates emissions. An older diesel vehicle will emit about hundred times more than petrol vehicles. Likewise, a small fraction diesel vehicles with the filter removed can tip the balance on the largest source of particulates emissions from petrol to diesel in the future. For diesel vehicles the consequences of problems with the filter are much larger than for petrol vehicles.

The current particulates matter emission factors for petrol vehicles are based on measurements on vehicles in use. It is expected that the particulates emissions from the consumption of lubricants is incorporated in the emission factors of around 5 mg/km of petrol cars. These numbers are higher than results from new petrol cars, with indirect injection. Although the increase in oil consumption after 100 000 km is well known, there is limited information on the contribution of oil burning to the total emission. Under the assumption of a typical increased lubricant consumption of 1 liter per 5000 km, i.e., 200 mg/km, it may mean that a substantial part of the particulates emission of 5 mg/km is unrelated to the injection technology. Moreover, very likely it is strongly dependent on the type of lubricant and the type of wear causing the increase in lubricant consumption.

In the light of brake, tire, and road wear emissions, in the order of 25 mg/km in urban use, the particulates emissions from the tailpipe is a minor source of generic particulate emissions. Currently, European air-quality standards make no distinction between the type of particulate matter PM10. Larger dust specks are as relevant for this standard as the small solid particles and polyaromatic hydrocarbons from the exhaust gas. In this respect, the tail-pipe particulates emission of petrol cars were, and will remain, a small source. Even within traffic emissions, the expected reductions, and possible increases, with the introduction and evolution of GDI technology are of little concern for the current European air quality regulation. Nevertheless, due to this increasing GDI share, the contribution of PM emissions as part of the total PM emission, needs attention.

2.3 Tail pipe emissions

In a combustion engine a relative small share of petrol fuel is not burnt.
Petrol engines with direct fuel injection (GDI) have a relative short mixing time available for the air and fuel fractions. Consequently the air-fuel mixture is not fully homogeneous and in the combustion particles are generated and subsequently emitted.

2.3.1 Particulate Matter (PM)

Due to inhomogeneous mixtures of air and fuel, certain quantities of particulates are emitted. PM emissions of a vehicle are commonly measured on a chassis dynamometer (not on the road) and normal PM emissions of a GDI engine are in the range of 0.1 to 6 mg/km. Cold start conditions, dynamic engine conditions and higher vehicle speeds generally generate relatively high PM emissions [1].

2.3.2 Particulate Number (PN)

According to the PMP measurement protocol for solid particles in the size range of 23-1000 nm are counted and reported in particles per km (#/km). Petrol engines with indirect fuel injection (or port fuel injection, PFI) generally have a lower PN emission than GDI vehicles because the available time for mixing of the air-fuel mixture is relatively long which results in a relative homogeneous air-fuel mixture. Most PFI engines emit below the Euro 6c PN limit value of $6 * 10^{11}$ #/km.

PN emission levels of GDI engines mainly depend on engine and fuel spray conditions (cold or hot start), the road type (urban/rural/motorway) and driving style. They are in the range of $1 * 10^{10}$ to $1 * 10^{13}$ #/km [1], [12], [14], [16].

Most GDI vehicles exceed the type approval PN limit value of 6 * 10^{11} #/km in the NEDC test with a cold start, see Figure 4 and Figure 5. These tests were executed with petrol with different oxygen contents (due to blends with ethanol, MTBE, ETBE within the EN228 petrol specification) and show a minor dependency on these fuel types. Some error bars of fuels are larger than the differences between fuels.

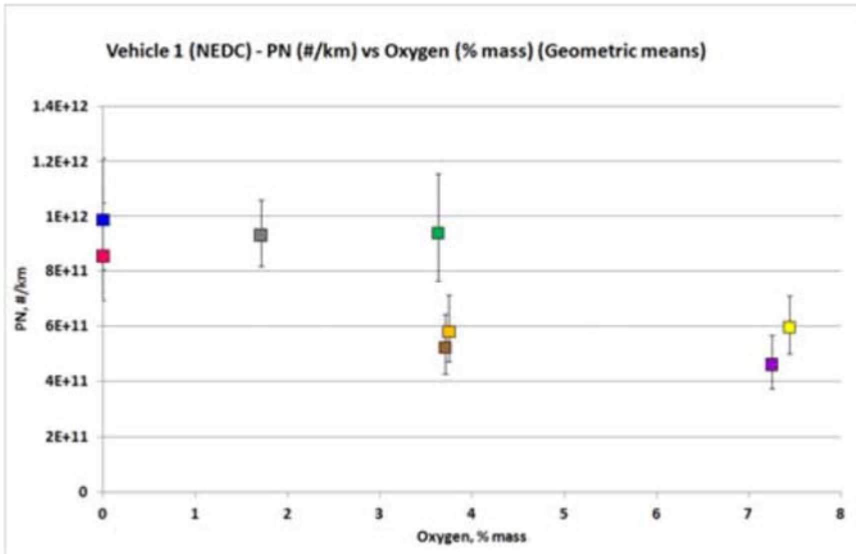


Figure 4: PN emissions of a Euro 4 GDI vehicle. with different fuels (source CONCAWE).

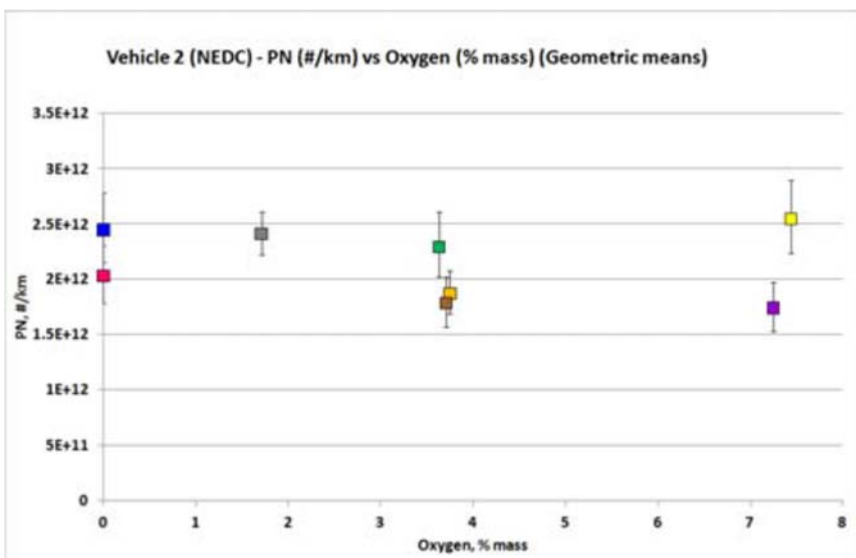


Figure 5: PN emissions of a Euro 5 GDI vehicle. with different fuels (source CONCAWE).

In Figure 6 the relationship of PM and PN of different Ford engine technologies are shown.

For PFI and GDI petrol engines this PM-PN relationship correlates good but scatters more at lower values. GDI and some PFI vehicles with 2009 technology cannot meet the Euro 6c PN limit value.

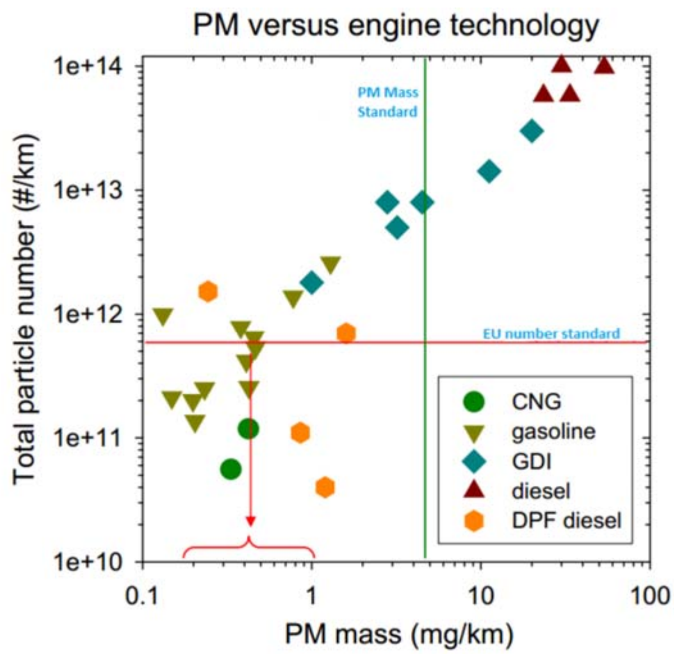


Figure 6: Particle Number vs. Particle Mass for various LDV engine technologies (source Maricq M., How are emissions of nuclei mode particles affected by new PM control technologies and fuels?, Ford Motor Company, Health Effects Institute Annual Conference, 2009).

2.3.3 *Cold start emissions of GDI vehicles*

After a cold start and in the warming up phase of a GDI engine the particulate emissions are relatively high because petrol fuel tends to stay liquid; There is not sufficient thermal energy for a complete evaporation of the fuel.
AECC [7] RDE tests at normal and low ambient temperatures (0 and -7 °C) show a 100% PN increase (from $7{,}5 * 10^{11}$ to $1{,}5 * 10^{12}$ #/km). Furthermore the PN emission in urban (cold) part of the test cycle is relatively higher, see Figure 7.

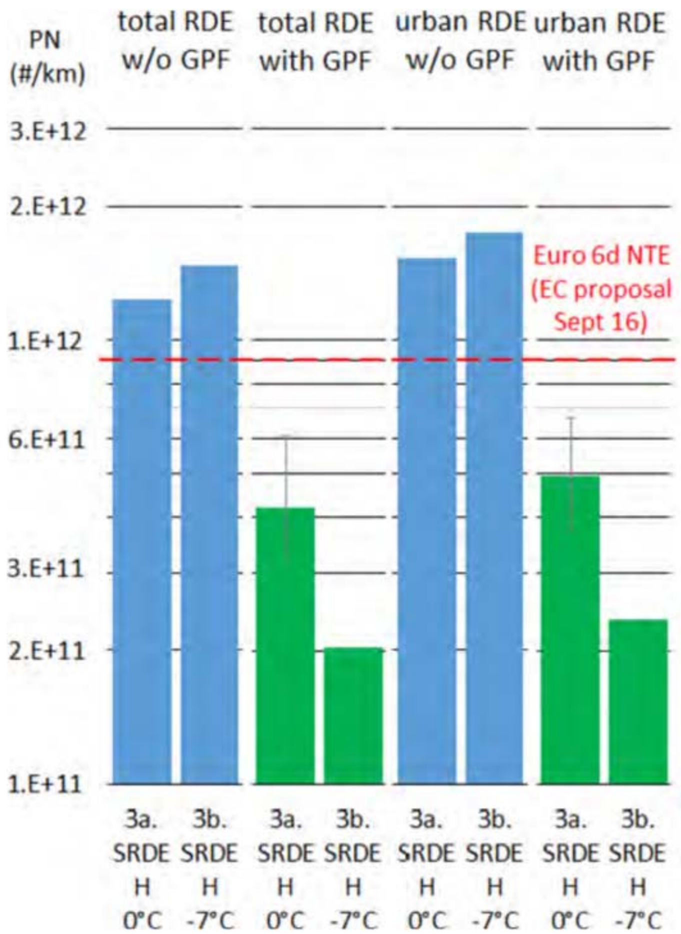


Figure 7: Total and urban RDE PN emissions measured on the dyno at low ambient temperatures (source AECC).

Current GDI engines are primarily optimized for power, driveability and thermal efficiency (i.e., low CO_2 emission) and they can meet the Euro 6b PM and PN limit values. In general their fuel injection technology have a major impact on formation of air-fuel mixtures and particulate emission, especially the PN emission. It is expected that improved petrol fuel injection technology in the cold start phase will result in a substantial decrease of particulate emissions. Potential improvements can be realized with double or triple injections per combustion cycle, increased fuel injection pressures, and improved fuel injector geometries.

2.4 Fuel composition effects on emissions

The quality of a GDI combustion mainly depends on the homogeneity of the air-fuel mixture. The main parameters in this mixing process are the operating temperature, the available time, air dynamics and the composition of the fuel. Fuel is a mixture of different hydrocarbons and it can be ranked on the basis of the chain length and the structure of the hydrocarbons, reflected in the remaining fraction at certain boiling temperatures.

The JAMA fuels and lubricants committee reported [9] a relationship between fuel composition and PN emissions of GDI vehicles. Petrol with higher rates of heavy fractions emit more PN emissions which is caused by relatively poor mixing of air and fuel.

In order to normalise the PN emission JAMA proposes a so-called PM-index which is a related to the share of evaporated fuel at 130, 150 and 170 °C. Jama defines a light fuel by means of the evaporation rate at 150 °C of > 84%. A high PM-index of 2.5 (the total scale ranges from 0.0 to 3.0) is related to a fuel with a high share of heavy fractions E150 < 84%).

The JAMA test data in Figure 8 show an increase of the PN emission of GDI vehicles with a factor 4 at a PM-index raise of 1.1 to 2.5. The PN emission of the GDI-PFI vehicle (vehicle C) is less sensitive for fuel quality.

JAMA proposes application of reference fuel for RDE certification.

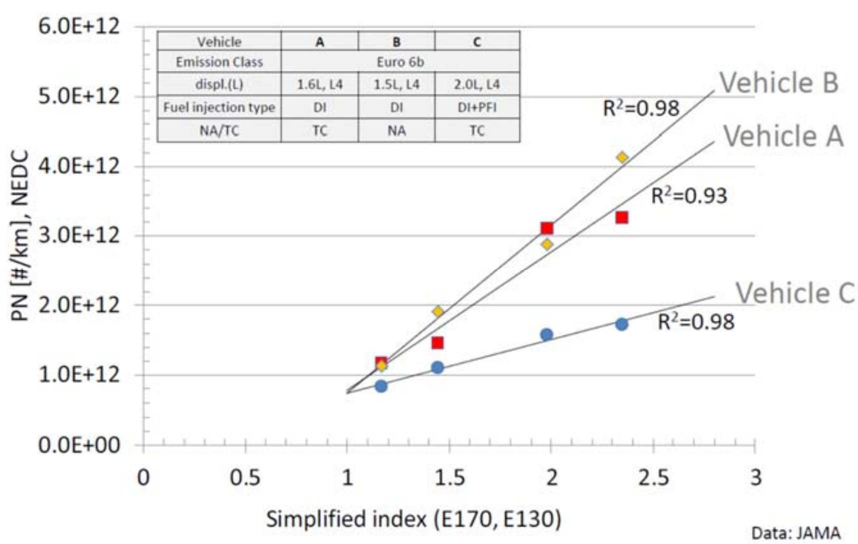


Figure 8: Different fuel compositions (expressed with the simplified PM index) and NEDC PN emissions (Source Jama) of GDI and PFI engines. Source JAMA.

CONCAWE [12] performed a study of 2 different GDI vehicles without GPF (Euro 4 and 5, see Figure 4 and Figure 5) and they reported no or minor PM and PN effects of different fuel compositions (Oxygen share variations from 0 to more than 7 % mass and RON varies from 95 - 101).

ACEA published their view on fuel quality and PN emissions of a number of GDI vehicles with different GPF types in a presentation [26]. Fuels with heavier fractions cause up to 3.5 times higher PN emissions in RDE tests which is in line with other publications such as the JAMA Figure 9.

2.5 In use effects on emissions

Johnson [13] summarised in ‘Vehicular Emissions in Review’ several items which affect strongly the in-use PN emission of GDI engines. Fuel injectors with deposits resulted in a 2,5 times higher PN emission than clean injectors.

Furthermore, the next items result in increased PN emissions:
- Deposits in the cylinder
- Misalignment of the injectors
- Fuel pump variations
- Long idling times

On the basis of these findings it is clear that the quality of the fuel spray and other factors strongly influences the PN emission of a GDI engine.

AVL [11] reports a direct relationship of PN emissions of GDI vehicles in RDE trips and transient operation, see Figure 9. Especially an aggressive driving style results in a sharp increase of the PN emission.

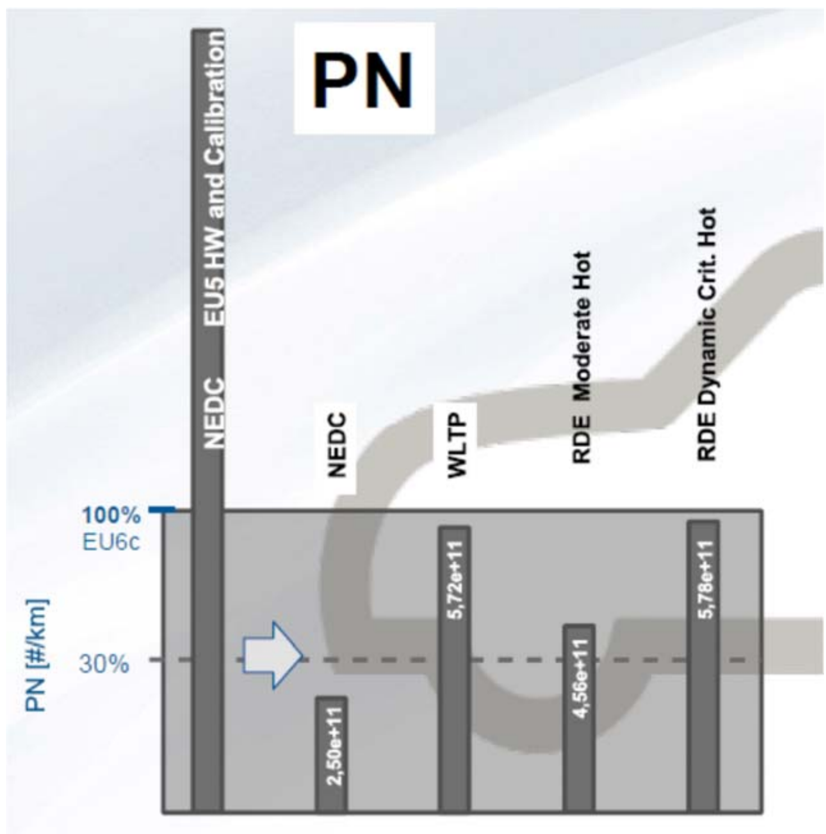


Figure 9: PN emissions of a 1600 kg SUV with 1.0 ltr GDI engine (source AVL)

Engine oil consumption is mainly related to the engine construction and condition. Pistons, piston rings, intake and exhaust valves, valve stems and operating principle are primary factors which affect oil consumption. The GDI engine concept does not yield specific new items which may lead to higher oil consumption than other engines.

2.6 PN emission potential

Several experts and manufacturers report a substantial potential for improvement of the PN emission of GDI vehicles.

General Motors [17] states that over 90% PN reduction of a GDI vehicle is possible by optimisation of the following items, see also Figure 10:
- Calibration update (fuel injection strategies) -50%.
- Fuel injection system upgrade (injectors with multiple injections) -25%.
- Base engine update (less oil consumption) -15%.
- Controls update -5%.

All proposed measures are designed to improve the air-fuel mixture and to avoid inhomogeneity's. GM needs six years (2017-2022) for implementation of these engine and product developments. However, they have not announced the application of GPFs on their production models, unlike other manufacturers, so the status of the applied GPFs and observed effects remain unclear.

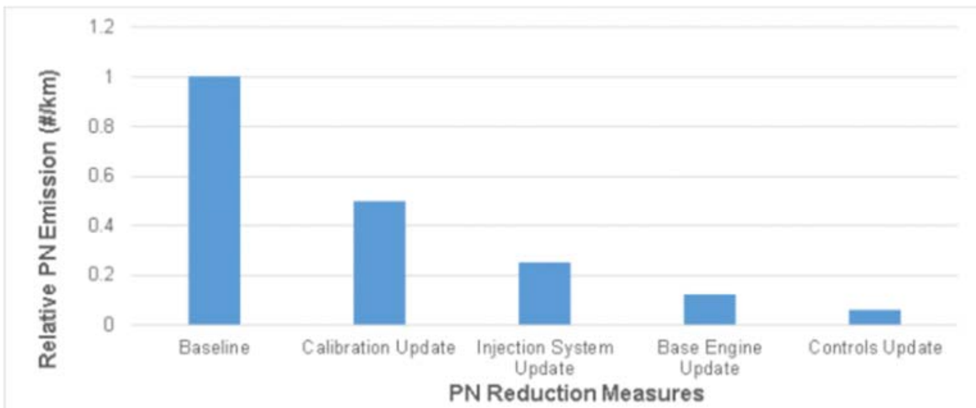


Figure 10: Impact of PN control measures on PN reduction (source GM, September 2016).

After detailed study and research of RDE optimisation strategies (see Figure 9). AVL [11] states: "With respective refinement, even critical combinations engine/vehicle can meet RDE-PN w/o GPF" .

Audi's all-road brake plug in hybrid concept (2.0 litre EA888 Gen 3 engine) is equipped with technology that combines direct fuel injection and indirect fuel injection into the intake manifold. Audi states this technology is sufficient to meet Euro 6 particle limits without the use of a particulate filter.

All above proposed improvements will substantially improve the PN emissions of GDI vehicles but will probably not lead to PN improvements in all engine conditions because engine optimisations generally lead to compromises and because type approval tests are usually carried out under optimal conditions (optimal fuel, no wear).

The technical fuel injection concept of GDI vehicles is very sensitive. Small fuel injection spray variations may lead to deviating local air-fuel mixtures which can result in different PN formation.

Furthermore deterioration effects such as in-cylinder carbon deposits and injector fouling heavily influence fuel injector spray patterns. On the long term, due to engine wear and fouling, it is expected that GDI vehicles with initial low PN emissions will have a substantial increased PN emission (in analogy with diesel vehicles without DPF).

2.7 Conclusions PM and PM emissions of GDI engines

Based on the reviewed literature, it can be concluded that PN emissions of GDI engines in real world operation can vary a lot and hence exceed type approval values.

In particular the following influences are known:
- Petrol with a higher share of heavy hydrocarbons: up to a factor 4 higher PN emissions
- Test cycle or drive behaviour: up to a factor 2 higher
- Injector fouling: up to a factor 2.5 higher
- Oil consumption may rise over lifetime, which will likely contribute to higher PN emissions

3 Application of Gasoline Particulate Filters (GPF)

3.1 Status development and implementation as per 2017

GPF technology is relatively new but the applied materials (porous honeycomb structures, precious metals and carrier materials) are well known for decades. Separate units or integrated with a TWC as well as different locations (closed coupled (CC) or under floor (UF)) allow different exhaust configurations, these are:

1. CC-TWC + uncoated CC-GPF (two bricks in one unit).
2. CC-TWC + uncoated UF-GPF (two bricks in two separate units).
3. CC-TWC + coated UF-GPF (two bricks in two separate units).
4. CC-GPF with TWC coating (one brick in one unit).

In essence all petrol engines can be equipped with a GPF, there are no major technical constraints. Application of GPFs may cause some increased engine backpressure which needs attention in the engineering process. Special attention must be paid to the passive regenerations of the GPF because this must take place during engine decelerations. Sufficient oxygen and certain operating temperatures are then available to realise complete regenerations of the GPF.

The news about implementation of GPFs is diverse. Currently only Volkswagen[25] and Mercedes[26] announced a gradual application of GPFs on all their European petrol vehicles.

The following information of PSA and Hyundai-Kia was published by Total[27].
PSA announced: *"For us, I think gasoline particulate filters are a question of when, not if," states Christian Chappelle, head of powertrain at PSA Peugeot Citroën. "We are now ready to introduce them in some parts of our portfolio. There's a lot you can do in-cylinder to reduce particulates, but we think there will be a practical limit, a bit like there was with diesel engines. There comes a point where the effort you're putting into the injection system will start to impact the efficiency. It will also begin to cost more than switching to a GPF."*

Hyundai-KIA announced in-cylinder solutions: *There's no doubt this will present a huge challenge to powertrain engineers, but the general consensus is that OEMs could tackle it with in-cylinder methods alone. "I think the strategy of most OEMs will be to fulfill the requirements of Euro 6C with internal measures," comments Dr Michael Winkler, head of powertrain at Hyundai-Kia Europe. "Adding a particulate filter increases the cost, which in the end the customer has to pay, and provides an additional source of backpressure. That's particularly a problem for gasoline, where the backpressure has a very negative impact on combustion. The exhaust gas is very hot and with raised backpressure you have more of it trapped in the cylinder, which can lead to knock." But there are a number of ways to reduce particulate formation in the cylinder. Improved turbulence, cam timing and fuel injection strategy are all part of the equation, but much of it is likely to focus on the delivery pressure and the design of the injectors themselves.*

[25] VW Press release ce39a318-6013-4e08-a606-2165d116579b
[26] 2017-03-18, https://www.daimler.com/innovation/specials/engineoffensive.html
[27] http://www.lubricants.total.com/news/new-gasoline-particulate-filters-gpf.html

“State of the art at the moment is around 200 bar,” says Winkler. “I think for Euro 6C this will be sufficient, but looking ahead to later emissions standards it may be that higher pressures will be required.” For fuel injection suppliers it’s a deceptively simple engineering task.

Total announced: *It’s unclear yet what level of uptake there will be for GPFs, but it’s likely that most manufacturers will at least consider them as an option. In the USA, 38% of all cars sold now come with a GDI engine, while the global GDI market will be into the tens of millions by the time Euro 6C and the EPA’s rumored particulate number restriction legislation come into effect. And that means that the potential market for GPFs is a very large one indeed*

AVL List GMBH published their view on RDE and GPFs [11] : In the detailed presentation on sheet 47 the statement ‘*With respective refinement, even critical combinations engine /vehicle can meet RDE-PN w/o GPF’.*

General Motors [17] expects to realize a 95% PN emission reduction of GDI engines without GPF but they need 6 years for a full implementation!

In order to meet Euro 6c RDE-PN limit values it is expected that most manufacturers need a GPF on short term. On the long term it is expected that they will optimize the internal combustion of a GDI engine which may lead to vehicle configurations without a GPF.

3.2 Coated and non-coated GPFs

Non-coated GPFs (they do not contain precious metals) can be mounted in addition to a TWC. They either can be installed as a closed coupled (CC) device or under floor (UF) device. For the latter the relatively low operating temperatures and weak regeneration performance is point of attention.

Coated GPFs (with precious metals) are named 4WC’s. On the long term it is expected that most vehicles will be equipped with a 4WC because the package in the exhaust system is relatively small and at a favourable position (near the engine with the highest available temperature).
From regeneration perspective the coated GPF has a high performance because the precious metals decrease the temperature level of this process.

3.3 PN emissions, filtration efficiency and particle size

GDI engines without GPF emit particles in the size range of 10 to 400 nm [14][16] which can be captured by GPFs. GPFs have a certain pore structure which heavily determines the GPF filtration efficiency which depends on:

- The space velocity
- The pore size
- The pore structure
- The soot load
- The operating temperature

Bigger pores result in a relatively low engine backpressure (and a relatively low CO_2 emission) which is preferred by manufacturers but it also lowers the filtration efficiency.

Figure 11 shows the relationship of different GDI PN emissions and different GPF filtration efficiencies. In case of a Euro 6b vehicle with a PN emission of 6.0 * 10^{12} #/km a GPF with a 85% filtration efficiency is needed to comply with the Euro 6c RDE PN limit value of 9.0 * 10^{11} #/km. In order to comply with the Euro 6c PN limit values vehicle manufacturers only have to install GPFs with a typical minimum filtration efficiency of 85% on a Euro 6b vehicle; No fuel injection optimization is needed. With this 85% GPF filtration efficiency experts expect a negligible increase of the engine backpressure and CO_2 emission. Higher filtration efficiencies of equal sized GPFs will probably result in increased CO_2 emissions.

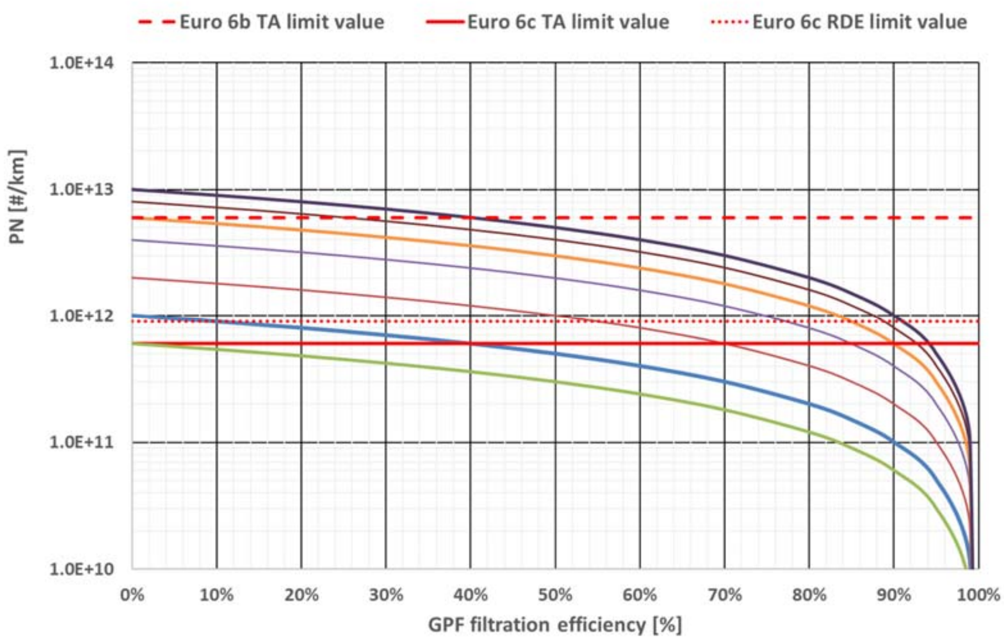


Figure 11: Sketch of PN tail pipe emissions of vehicles with different PN emissions and different GPF filtration efficiencies (1).

A dedicated GPF test program was initiated by the Swiss CCEM. Five GDI vehicles, one diesel vehicle with DPF and four different GPFs were tested in the GasOMeP project. In Figure 12 the PN emissions of the vehicles without and with GPFs are shown. All GDI vehicles without GPF emitted in the WLTC tests less than 6.0 * 10^{12} #/km. On the basis of a PN emission of 4 * 10^{12} #/km a GPF must have at least a particle count based efficiency of 85% to meet the limit value of 6 * 10^{11} #/km.

GPF1 was also tested on a second vehicle and yield a similar result. From these results it can be concluded that PCFE is not related to the GPF coating. Probably the pore structure and the dimensions of the GPFs are more related to PCFE.

From the four GPFs only one coated (GPF2) and one non-coated (GPF1) type reduced the PN emission below 6.0 10^{11} #/km. The PN filtration efficiency ranges from 78 to 98%, see Figure 13. Although the filtration efficiencies of GPF3 and GPF4 are 80 and 78% these vehicles could not meet in WLTP tests the Euro 6c type approval limit value. This shows that the quality of the combustion and the filtration efficiency of the GPF combined yields the PN test result. The diesel vehicle (V6) with DPF performed well below the Euro 6 PN limit value of 6.0 * 10^{11} #/km.

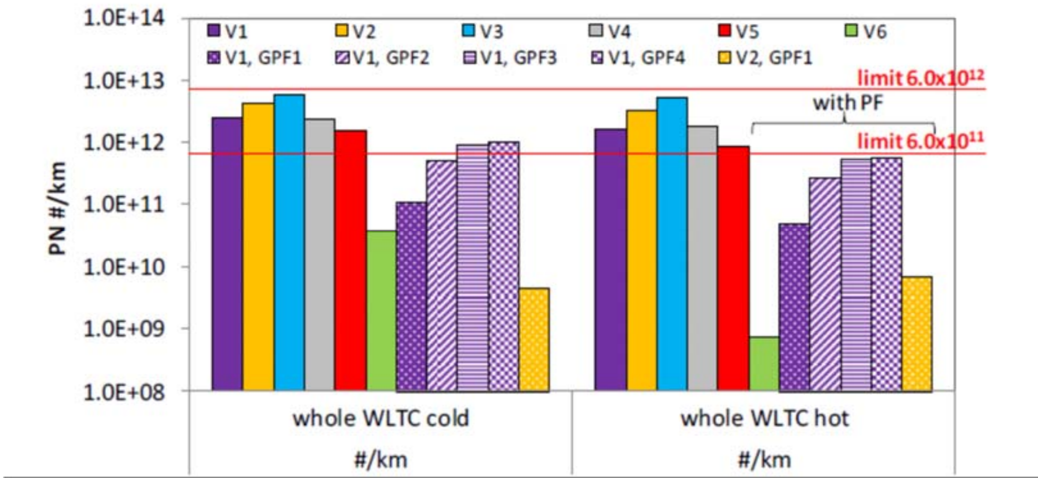


Figure 12: WLTC PN emissions of 6 GDI vehicles. On vehicle 1 and 2 four different GPFs were tested (source GasOMeP project, Switzerland).

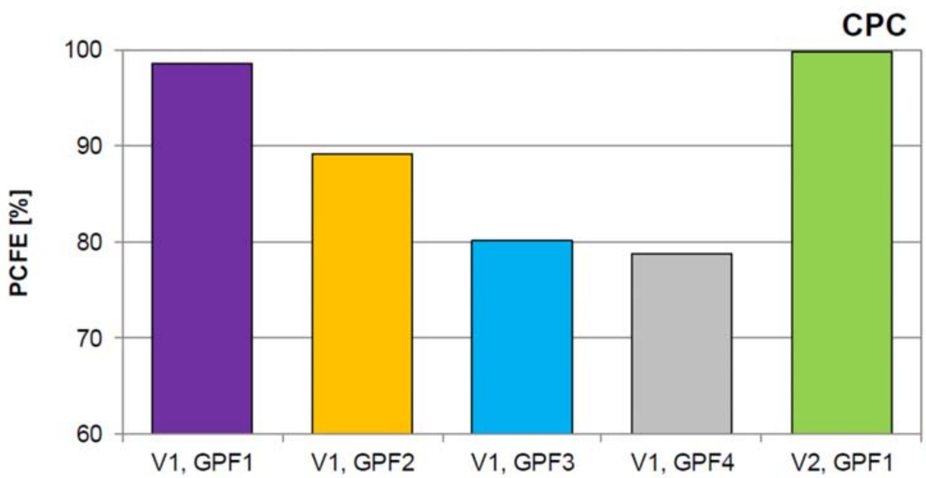


Figure 13: PN emission filtration efficiencies of four different GPFs in WLTC tests, GPF 1 was tested at two vehicle types (source GasOMeP project, Switzerland).

In Figure 14 filtration efficiencies of two coated (GPF2 and GPF 3) and two non-coated GPFs (GPF1 and GPF4) at different constant velocities are shown. At the lower speeds for all GPFs the PN filtration efficiency is above 95% which is very promising for urban traffic emissions. For some GPFs the PN filtration efficiency decreases at higher speeds but it still is above 90%. The question remains if such filters will be applied by the car manufacturers. In [26] ACEA reports somewhat lower filtration efficiencies, namely in the range of 60% to 85% (one vehicle with 60%). JAMA present a figure with a band which indicates that filtration efficiency could get as low as 60% (new filter / low mileage) but also up to 90% or more if ash and soot accumulates in the GPF. Refer to [27].

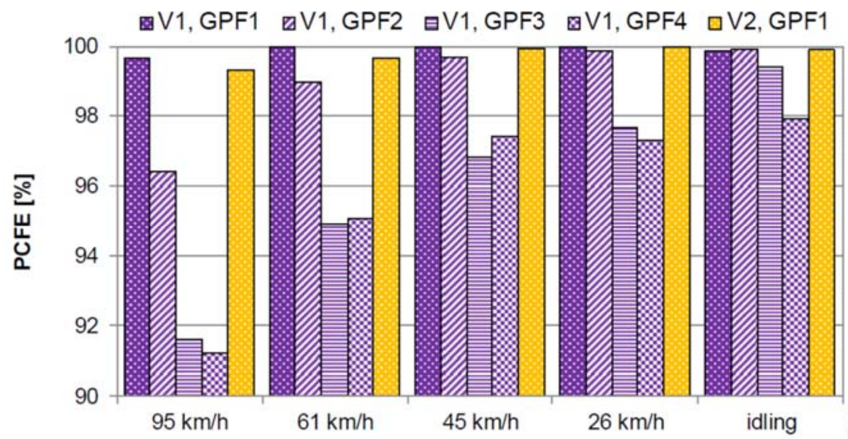


Figure 14: PN emission filtration efficiencies of four different GPFs at constant velocities, GPF 1 was tested at two vehicle types (source GasOMeP project, Switzerland).

In the GasOMeP project the filtration efficiencies over the total particle size range of the GPFs were investigated in detail. At a constant vehicle speed of 95 km/h the filtration efficiency of GPF1 (mounted on vehicle 1) was near 100% for the smallest particles (2 – 30 nm), see Figure 15. Above a particle size of 30 nm the PN filtration efficiency reduced somewhat to 99.

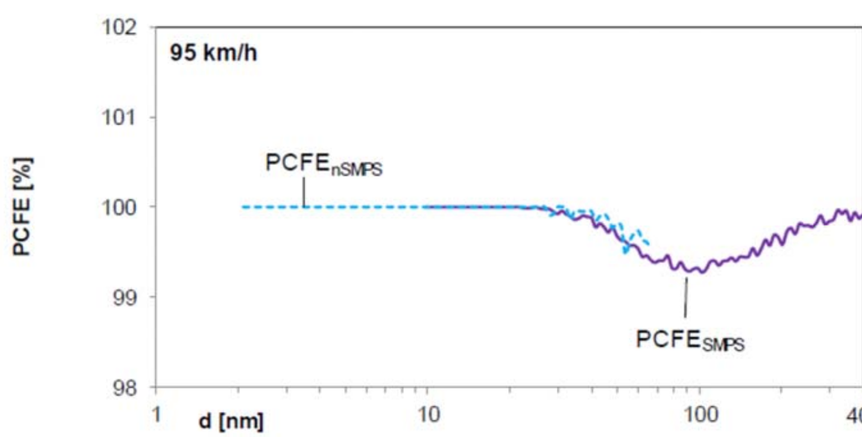
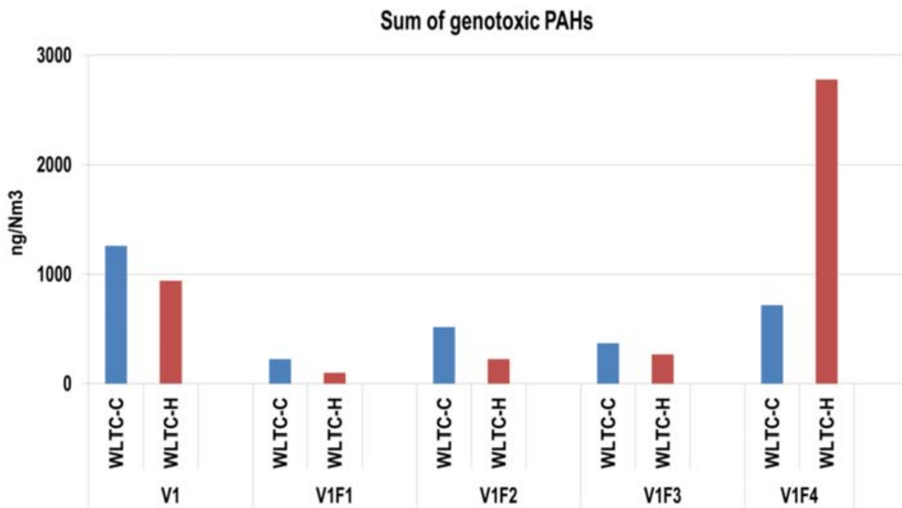


Figure 15: PN emission filtration efficiencies over the total particle size range of GDI vehicle 1 with GPF1 @ 95 km/h (source GasOMeP project, Switzerland)

3.3.1 *Unregulated emissions*

In addition to regular PM and PN emissions the emitted fractions can be chemically characterized. Swiss researchers installed in the GasOMeP project in addition to the standard three-way catalyst (TWC) coated and non-coated GPFs on one vehicle [15] and measured (except one hot test) a serious reduction of polyaromatic hydrocarbons (PAH) in WLTC tests. Polyaromatic hydrocarbons are associated with toxicity of exhaust gas particles, however, only as one of the many proposed mechanisms of the carcinogenicity of vehicle exhaust gas.

In case of one uncoated GPF the PAH emission increased which is not understood. Possibly stored chemical fractions were released later.



Euro5 + F1 + F2 + F3 + F4
(Ref. vehicle) (A –Noncoated) (A-Coated) (B-Coated) (B-Noncoated)

Figure 16: Genotoxic PAH emissions of a Euro 5 GDI vehicle tested with four different GPF types.

The GasOMeP team concludes that a toxic equivalent concentrations of GDI vehicles <u>with and without these GPF types</u> are several times higher than a Euro 6 diesel engine with DPF.

JRC investigated numbers and sizes of solid and volatile particles of GDI vehicles in detail [23]. One GDI vehicle was also tested with a GPF.
In order to classify the particles several CPC's were applied in NEDC and CADC tests on the chassis dynamometer.

PN emissions in the following particle size ranges were measured:
- > 23 nm (only solid)
- 10 – 23 nm (only solid)
- 4,5 – 10 nm (only solid)
- > 3,5 nm (solid + volatile)

In Figure 17 to Figure 20 the PN emissions per size class of different vehicles with different technologies are shown. From the three GDI vehicles the standard PMP-PN emission (particle size > 23 nm) is in most conditions approximately 80% of the total solid PN emission. The residual 20% PN emission is related to smaller solid particles (psize is 10 – 23 nm). Two vehicles emitted in the motorway part of the CADC test higher shares (30%) of 10 – 23 nm particles. Some vehicles emitted at the motorway substantial amounts of volatile particles.

If legislation would be adapted and particles in the size range of 10-23 nm would be added to the current PMP method it is expected that the PN emission of a GDI vehicle will increase 20-25%; With the current type approval limit value of 6 * 10^{11} #/km, the severity of the test increases in the same range.

The application of the GPF resulted in a nearly complete filtration of the 10 – 23 nm solid particles.

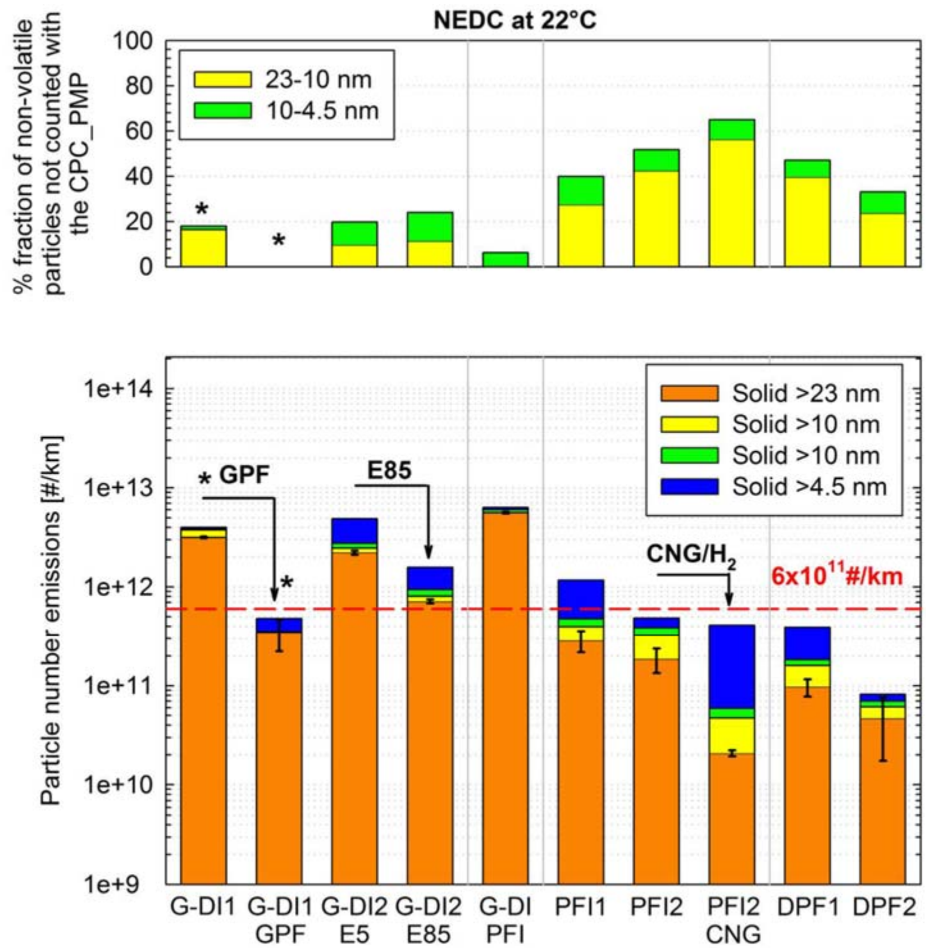


Figure 17: Particle number emission rates of the different vehicles tested over the NEDC (bottom panel) and fraction of sub-23nm non-volatile particle counts not detected with the PMP CPC (top panel). In the bottom panel, orange bars correspond to number emission rates of non-volatile particles determined with the CPC having a d50 at 23 nm, yellow bars show the excess emissions measured downstream of the VPR with the CPC having a d50 at 10 nm (* or 6.5 nm in the case of G-DI1), green bars indicate the excess emissions measured downstream of the VPR with the CPC having a d50 at 4.5 nm, while blue bars show the excess emissions of thermally untreated samples measured with the CPC having a d50 at 3.5 nm. Error bars stand for ± one standard error of the measured number concentrations according to the regulatory procedure (d50 at 23 nm). In the top panel, yellow bars indicate the fraction of particle concentrations measured with the CPC at 10 nm not counted by the CPC at 23 nm, while green bars correspond to the excess fraction of particle concentrations measured with the CPC at 4.5 nm not detected by the CPC at 23 nm (source JRC).

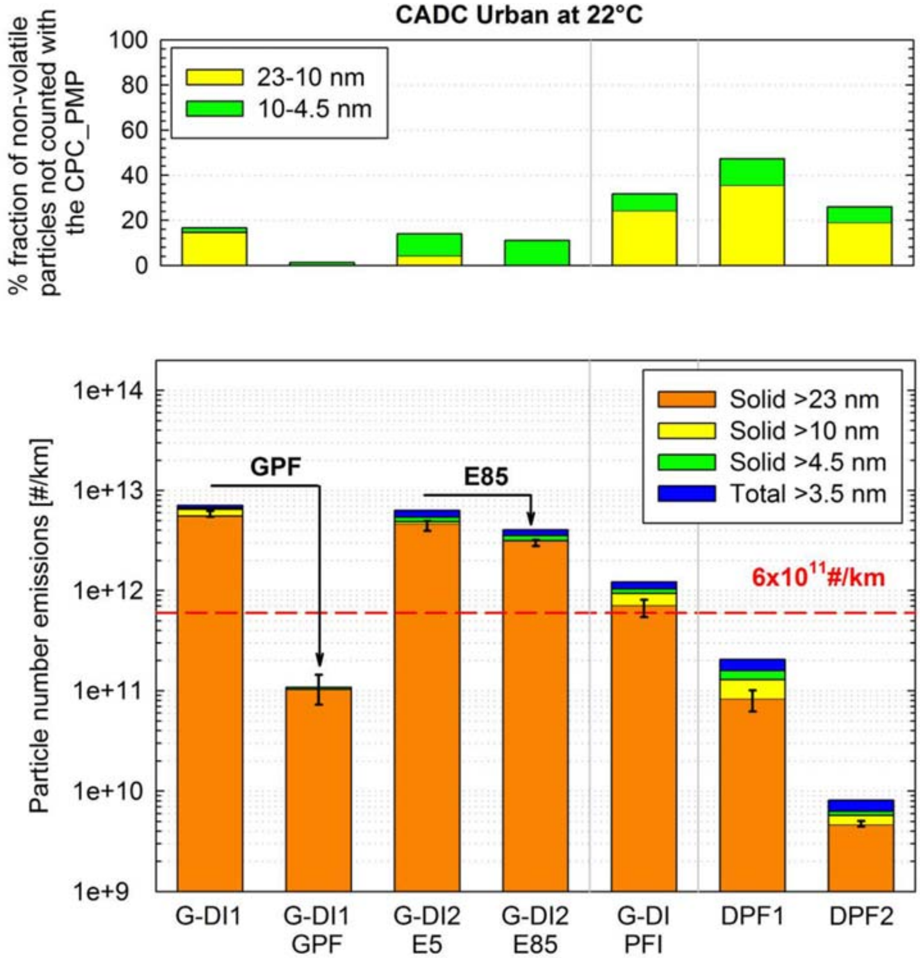


Figure 18: Particle number emission rates of the different vehicles tested over the urban phase of the CADC (bottom chart) and fraction of sub-23nm non-volatile particle counts not detected with the PMP CPC (top chart). Explanations as in Figure 18.

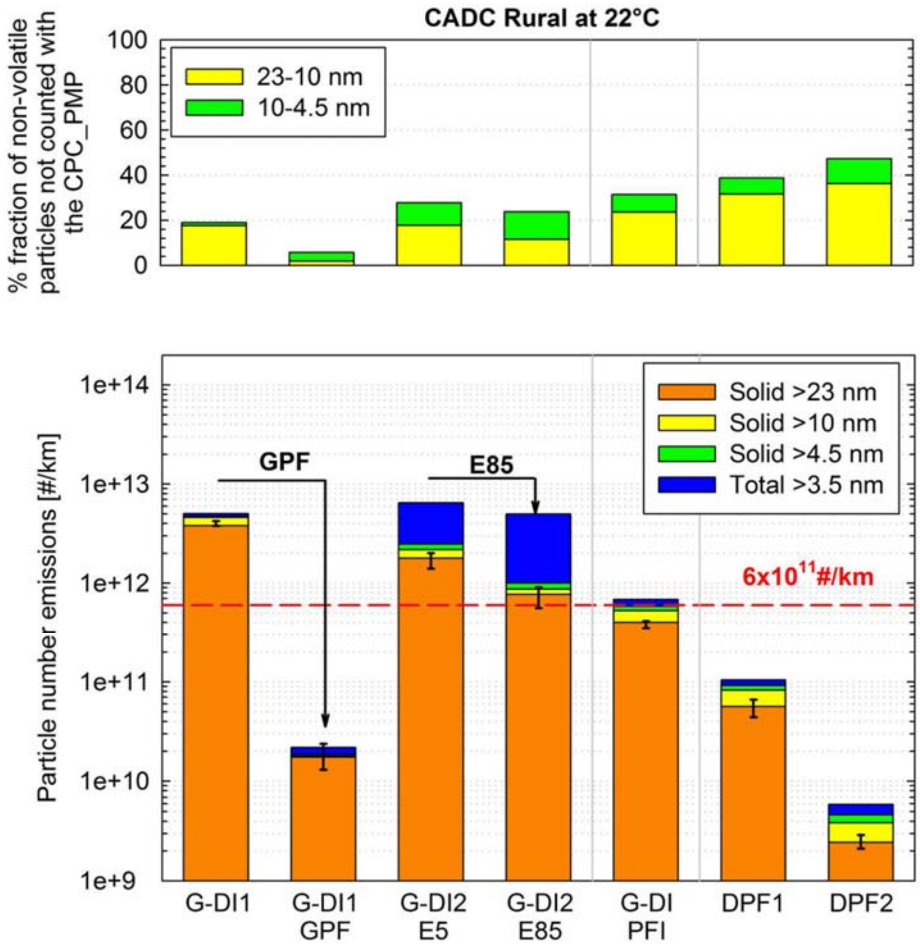


Figure 19: Particle number emission rates of the different vehicles tested over the rural phase of the CADC (bottom chart) and fraction of sub-23nm non-volatile particle counts not detected with the PMP CPC (top chart). Explanations as in Figure 18.

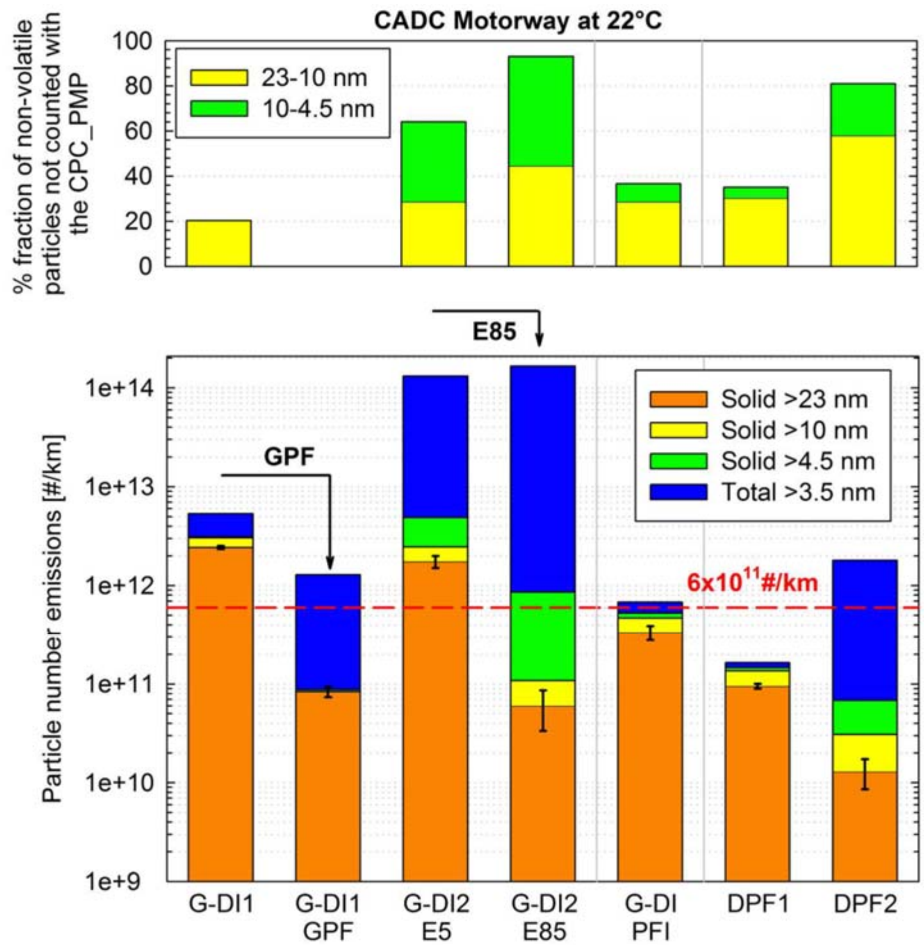


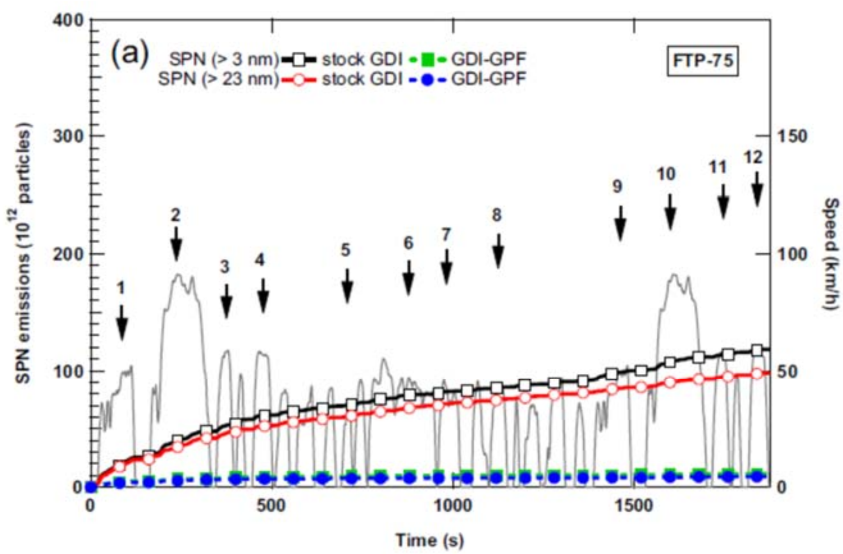
Figure 20: Particle number emission rates of the different vehicles tested over the motorway phase of the CADC (bottom panel) and fraction of sub-23nm non-volatile particle counts not detected with the PMP CPC (top panel). Explanations as in Figure 18.

3.4 Regeneration

During vehicle operation soot is stored in the GPF and this soot can be oxidised as the required temperature and sufficient oxygen concentrations are available. For petrol engines GPF regenerations typically take place during decelerations of the engine speed. Compared to the regeneration of a DPF the regenerations of a GPF are very short and more frequent. Several stakeholders mentioned the regeneration process of the GPF as a point of attention [19]. The PM emission of a GDI vehicle is relatively low (compared to a diesel engine) and a relative small amount of soot is stored on the GPF. Given a GPF operating temperature of 300 to 700 °C, in every deceleration soot oxidation is possible. A retrofit under floor uncoated GPF may possibly not reach the required regeneration conditions because the operating temperature is relatively low.

Chan et al [10] report test results of a Ford Focus 2.0 GDI vehicle which was tested with and without coated GPF in the FTP-75 and US06 chassis dynamometer test cycles. It results raise some concern on the emissions of small particles with GPF on the motorway.

Special attention was given to the regeneration process of the coated GPF. Solid particles were measured in the size ranges > 23 nm and > 3 nm. In Figure 21 the modal mass results are shown. The FTP-75 test cycle represents vehicle use in urban and rural areas and the GPF was filtering continuously. Once the vehicle was brought in motorway operation in the US06 test cycle, after 3 minutes the >3 nm PN emission increased rapidly which is comparable with the CADC motorway PN emissions of JRC, see Figure 20. The cause of this increased >3 nm PN emission is unknown; Particles might be formed in a secondary process (i.e. in the dilution tunnel) or were stored in the GPF and released at higher temperatures. The overall conclusion is that a GPF performs very well in urban and rural conditions. On the motorway a GPF still has a substantial efficiency for >23 nm particles, the relative high emission of the smaller particles (3-23 nm) requires further research. This effect has, so far, not been reproduced by others.



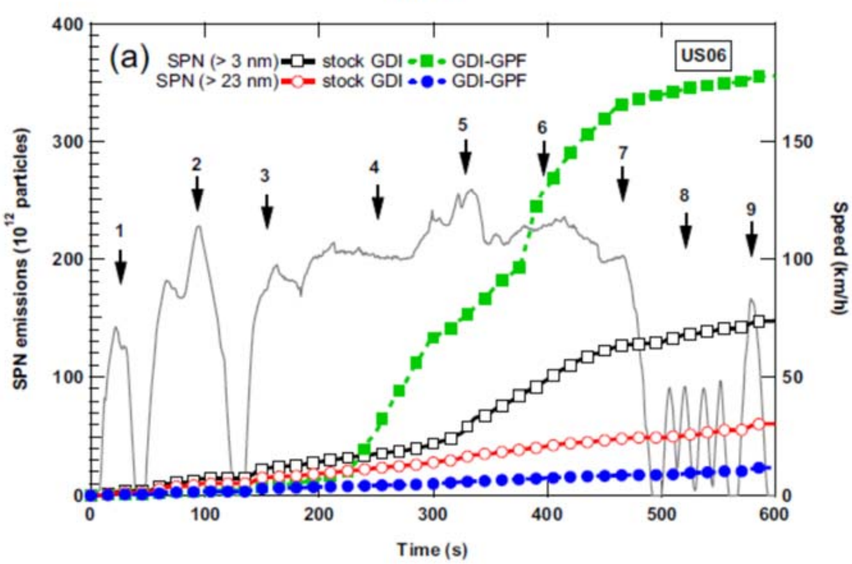


Figure 21: FTP-75 and US06 PN emissions (>23 nm and >3 nm) of a Ford Focus 2.0 GDI with and w/o GPF (source Chan et al.)

3.5 Durability

The long term performance of a GPF is unknown. Possibly closed coupled filters behave different as the under floor filters. Combustion engines consume a certain amount of lubricant which is mainly burnt. These lubricants contain a small amount of metals and minerals which are transformed to ash during a combustion. During a lifetime of a GPF it is loaded with ash. NGK shows in a case study [24] the long term filtration efficiency of a coated GPF. In
Figure 22 over 160.000 km the PN emission of a GDI engine with a coated GPF decreases from $2*E^{11}$ to $5*E^{9}$ #/km.

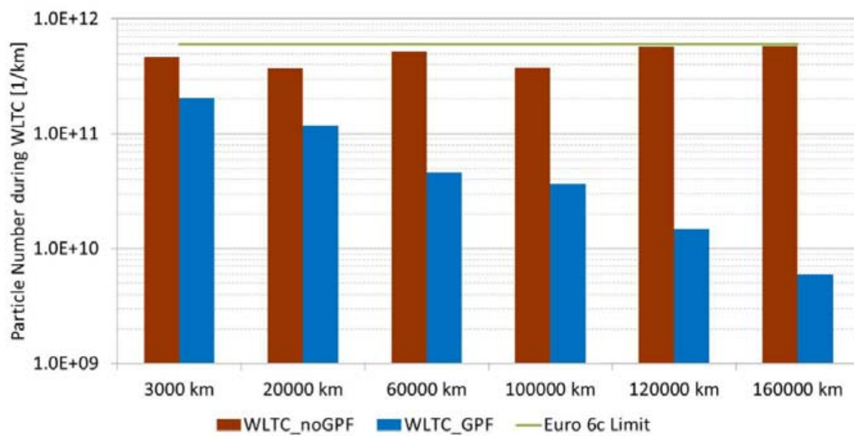


Figure 22: Tailpipe PN emissions in WLTC tests with and without underfloor catalysed GPF on a 1.8 l GDI Euro 5 engine measured at different mileages (source NGK).

General Motors [25] tested two Opel Zafiras with uncoated GPFs, one in a closed coupled configuration and one in an underfloor configuration. In the course of a GPF-lifetime (160-200 thousand km) 17 to 21 g ash was stored in the GPF and the PN emission of the vehicles decreases substantially; The GPF filtration efficiencies increased from 73 to 91%, see Figure 23. These vehicles have a lubricant consumption of 1 litre per 40.000 km. In case of a higher lubricant consumption one could imagine that GPF plugging is a real threat.

The increase of filtration efficiency over the lifetime, due to the deposition of ash, has been observed in different studies. Although it indicates a good durability of the GPF, it also may entail risks for maintenance issues and increase in fuel consumption.

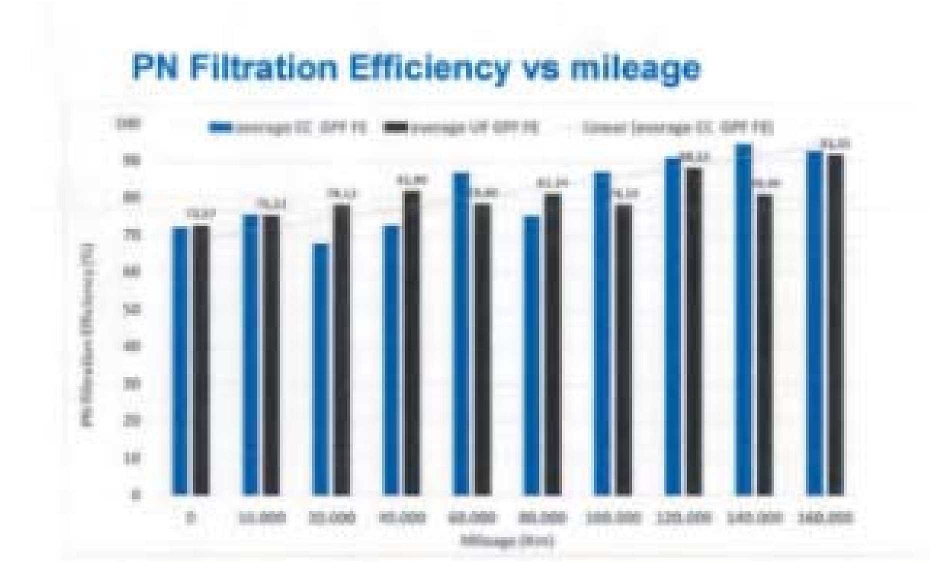


Figure 23: Tailpipe PN emissions in WLTC tests with 2 different GPF types (underfloor and closed coupled) of 1.6 l GDI Euro 6 engine (Opel Zafira) measured at different mileages (source GM).

4 Discussion

Market developments
At the moment GPF is the dominantly applied technology on new GDI vehicles as a result of the combined pressure of Euro-6 lab-based and RDE on-road standards for PN emissions. The high level of integration in the housing of the existing exhaust gas aftertreatment systems and the minimal or even no adjustments of the engine settings required, allow manufacturers to drop GPF application at any time if meeting the standards with engine optimization or improve fuel injection turns out to be possible.

Comparison of the performance of a DPF and GPF
Tests show, that DPFs generally have a very high filtration efficiency for PN of 99% or more. For GPFs however a range in filtration efficiency is generally seen of around 75% to 99%, although ACEA reports that this could be as low as 60% . For a diesel engines, DPF typically leads to a reduction from around $8 * 10^{13}$ #/km to around $4 * 10^{11}$ #/km. This is a decrease of the PN emission with a factor 200. The reason for the very high filtration efficiency of the DPF, is probably the soot layer which is generally present. The soot layer has a much finer pore structure as the ceramic honeycomb and will hence increase filtration efficiency.
In case of a petrol vehicle the PN emission of the GDI engine is around $4 * 10^{12}$ #/km. This can be reduced to a value in the range of $8 * 10^{11}$ to $4 * 10^{10}$ depending on the quality of the GPF.

It is uncertain how car manufacturers will specify the GPF in the future if it will be applied in series production. Will they select a GPF with a high filtration efficiency or will they go for the minimum to meet the limit values? The DPF is generally seen as a 'lock on the door' due to its high filtration efficiency. Even if engine out PM, PN emissions would rise due to a range of circumstances, the DPF will secure low tailpipe emissions. This is not automatically the case for GPFs. If the limit value is just met with GPF, and engine out emission would steeply rise (due to petrol type, engine fouling or wear), the tailpipe PN would also rise by the same factor. PN could then exceed the limit value substantially.

Robustness of GDI and GPF technologies
Optimisation of the PN emission of a GDI engine is feasible and it is expected that a significant improvement of these PN emissions is possible. From RDE point of view it cannot be estimated how robust these PN emissions are. A potential disadvantage of engine optimisation is the needed optimisation of PN emissions in the overall engine map. Probably certain sub optimal choices must be made which results in partial solutions. Furthermore, it is possible to switch off these active dedicated fuel injection strategies because these are actively controlled.

Moreover deterioration of fuel injectors will directly increase the PN emission. GPFs are passive elements which cannot be switched off and it is expected that this technology will lead to more robust real world PN emissions. But even with GPFs PN emissions may exceed limit values. This is due to the possibly relatively low filtration efficiency in combination with higher engine out PN emissions.
The latter can easily be caused by the petrol type, engine wear and driving behaviour.

The best way to secure low real world PN emissions is to systematically carry out ISC testing. Additionally it is important to widen the conditions for RDE testing (ambient conditions, fuel specs, drive style) and to have an appropriate Emissions Durability Period.

Accuracy of the PN measurements
Reliable PEMS measurement equipment fulfilling all RDE requirements is readily available. For PN-testing CPC based systems seem to have the highest accuracy but they are still relatively bulky. An important issue is the accuracy of PEMS equipment, as it directly impacts the NOx conformity factor: the final CF will be 1.0 plus a margin set to 0.5 in the 2nd RDE package that takes into account the assumed uncertainties introduced by PEMS equipment. This margin of 0.5 is wide compared to the (in)accuracy of current generation PEMS of well within ±30%. Setting absolute demands on PEMS accuracy and measurement procedures could help to make sure that systems are further improved and the uncertainty margin in the Conformity Factors can be reduced.

In order to reduce the safety margin of the RDE PN measurements a detailed assessment of the current available test equipment and RDE test is needed. The first attention should be given to the quality of the exhaust mass flow rate and secondly several PN test devices should be compared, also in a round robin and the results analyzed.

A first reduction of the safety margin for every vehicle from 0.5 to 0.3 is expected to be very ambitious and requires a big effort of all equipment manufacturers and independent testing partners. Different types of petrol and diesel vehicles should be tested and investigated in detail.

Potential options for accelerated introduction and implementation of GPFs
In case of an accelerated introduction of GPFs on the market one needs clear criteria and test methods which result in effective implementation of GPFs. Lower PN limit values or an alternative definition of measured particles as well as a reduction of safety margins are potential options for a more stringent test procedure.

- A reduction of the PN limit value is an easy, fast and effective manner to enforce application of GPFs. From the simulated results in Figure 24 a more stringent PN limit value of $9.0 * 10^{10}$ #/km for on road tests can be derived. This might be reached with a dedicated optimisation of the PN emission of the GDI engine and application of a GPF with a 85% filtration efficiency. It is expected that this more stringent PN limit value will ensure application of GPFs on a wide scale but manufacturers will need a certain lead time to improve PN emissions of their engines.

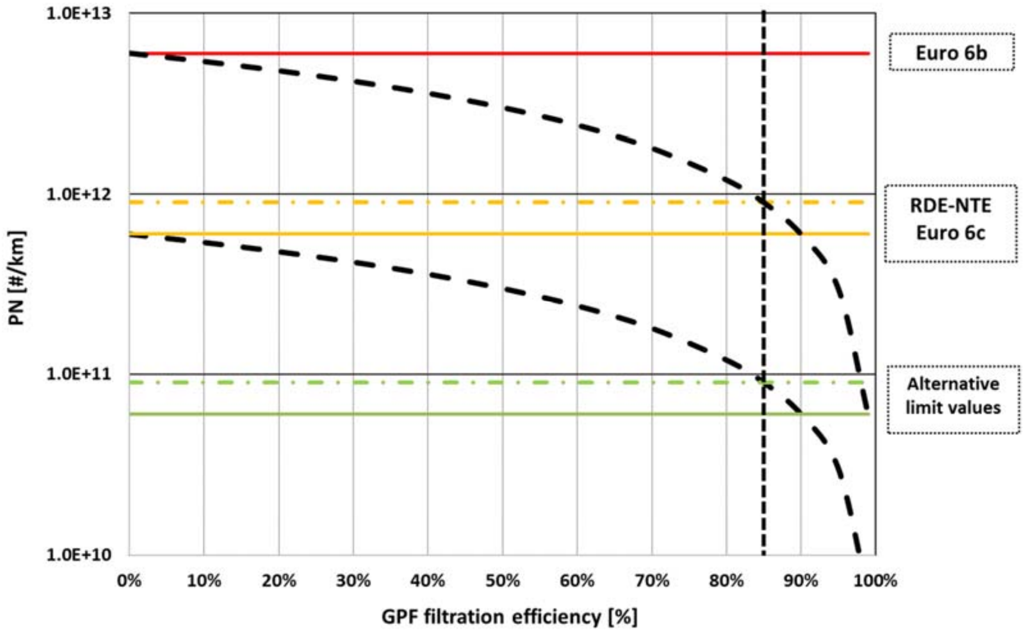


Figure 24: Simulation of PN tail pipe emissions of vehicles with different PN emissions and different GPF filtration efficiencies (2).

- Modification of the definition of a particle (> 10 nm instead of > 23 nm) will probably result in a 20-25% higher PN emission because more particles will be counted. In case of an equal PN limit value this is a way to set more severe requirements. However modification of an existing international measuring standard takes years because validation of the new equipment is needed. Furthermore it is expected that many stakeholders will not accept such high costs for setting more stringent PN limit values.

- Decrease of the safety margin of PN measurements from 1.5 to 1.0 with current PN test equipment will effectively lead to lower PN emissions, the RDE limit value will decrease from $9.0 * 10^{11}$ to $6.0 * 10^{11}$ which is a 33% reduction. Due to the different inaccuracies of the PN test procedure which will remain with this option the effective PN emission will decrease 33%. It is expected that this very easy and feasible option is insufficient to ensure application of GPFs because a 33% PN reduction might be realised with engine optimizations.

Potential practical weakness of GPFs

In the field some (older) petrol engines have a high lubricant consumption of one litre per 1000 to 3000 km. If only a fraction of this oil results in particulates the increase of PM emissions is substantial. Currently there is limited view on the effects of this lubricant consumption on the condition of a GPF. One could imagine that GPFs of these engines will plug fast because the metals of the lubricant will be stored in the GPF. In that case it is expected that some GPFs will be removed (by owners) in the field because this is the easiest and cheapest solution for car owners.

Repair of an engine with a high lubricant consumption is in most cases too expensive. If the GPF also acts as 3-way catalyst, high lubricant consumption may also compromise the efficiency of NO_x conversion, because of deposits of additives in the SCR catalyst.

5 Conclusions

The new Euro 6 and RDE standards for emissions of particulate matter for direct-injection for petrol vehicles require implementation of new technologies. Two options are available: optimisation of GDI technology (including fuel injection strategies) or implementation of GPFs. GPFs are a cheap and robust way to reduce emissions of particulate matter as well as particle numbers. In the course of 2018 all manufacturers selected the GPF to be the dominant solution: no new GDI introduction have been observed without GPF being applied. The durability and special circumstances that may occur in the on-road tests carried out by independent parties as well as the not yet available improved GDI technology, are the main reasons for application of GPFs.

Currently available test results report PN reductions with production vehicle GPFs of 80-90%, although it could be as low as 60%. GPFs seem to be a robust technology performing well in urban and rural traffic. On the motorway GPFs perform well on particle sizes >23 nm. However, some researchers report uncertainties with ultra-small particles (< 3 nm) and fuel quality dependencies.

Four potential GPF concepts are available (closed coupled or under floor and coated and non-coated GPFs). Currently there is limited understanding on the preferred concepts. In terms of regeneration performance the under floor non-coated GPFs might be more susceptible to plugging because they operate at lower exhaust gas temperatures. GPF filtration efficiency increases over time because accumulating burnt metal fractions of lubricants (so called ash) reduce the pore size or form a layer which increases filtration efficiency. Currently there is limited information on the long term filtration and possible plugging of GPFs.

If car manufacturers yet decide to drop the GPF technology new Euro-7 standards, that are now being discussed exploratory, or national financial incentives offer an opportunity to ensure GPF application on direct-injection petrol cars. Before a national incentive program can be introduced, it should still be investigated how high the standard should be, or a sufficiently high incentive can be provided and whether the registration of the values of fine dust particles numbers can be improved.

6 Abbreviations

CC	Close Coupled
CPC	Condensation Particle Counter
CVS	Constant Volume Sampler
DI	Direct Injection
DOC	Diesel Oxidation Catalyst
DPF	Diesel Particulate Filter
EGR	Exhaust Gas Recirculation
EOBD	Electronic On Board Diagnosis
FE	Filtration efficiency
GDI	Gasoline Direct Injection
GPF	Gasoline Particulate Filter
HD	Heavy Duty
IDI	InDirect Injection
LD	Light Duty
LNT	Lean NOx Trap
NEDC	New European Driving Cycle
NO_x	Nitrogen Oxides ($NO + NO_2$)
NTE	Not To Exceed
PCFE	Particle Count Filtration Efficiency
PFI	Port Fuel Injection
PM	Particulate Matter
PMP	Particulate Measurement Programme
PN	Particulate Number
PTI	Periodic Technical Inspection
SCR	Selective Catalytic Reduction
TWC	Three Way Catalyst
UF	Under Floor
WLTP	World harmonised Light duty Test Procedure
WLTC	World harmonised Light duty Test Cycle

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8 Signature

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