Emission compliance over the lifespan of a vehicle

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Abstract

With a lifetime of 15 years and more, many vehicles on the European roads no longer have to satisfy durability and in-service conformity requirements. If new cars satisfy stringent on-road emission standard, the risk of significant increase in emissions due to aging, malfunctions, poor maintenance and tampering will be substantial. Even a few percent failure average emissions could increase by a factor two or more. In the Netherlands this issue is investigated and a number of problems have been identified. Currently, the impact for air-quality is investigated, as are the options to stem the increase in emissions with age. Specifically, the failure and removal of diesel particulate filters and unnoticed malfunctions of the three-way catalyst system are investigated. Furthermore, options to address such problems are studied.

***Keys-words**: particulate emissions, NO_x emission, durability, Light Duty Vehicles, ISC, PTI, RDE.*

Introduction

Once new vehicles have entered the road the responsibility for the proper emission performance is not solely for the manufacturer. The owner, the garage, the type-approval authority, and the inspection authority should all together ensure that the vehicle retains a low environmental impact. Unlike safety, emissions have not been at the forefront in road worthiness of vehicles.

Table shows the (laboratory) pollutant emissions of light-duty vehicles as observed in new, type-approval tests have been reduced significantly over the past decade. However, under real driving conditions some emissions substantially deviate from their type approval equivalents. The real driving nitrogen oxides, or NO_x, emissions of diesel vehicles are currently the largest issue with regard to pollutant emissions and PM emissions are of great concern because DPFs are removed or fail due to, e.g., cracks in the ceramics.

Table 1: The different emission limits for PM and PN associated with the different Euro-classes for passenger cars with diesel and GDI engines (Gasoline Direct Injection).

	introduction dates		PM [mg/km]		PN [#/km]	
	new models	all models	diesel	GDI	diesel	GDI
Euro-4	1-Jan-2005	1-Jan-2006	25	-	-	-
Euro-5a	1-Sep-2009	1-Sep-2010	5	5	-	-
Euro-5b	1-Sep-2011	1-Sep-2012	4.5	4.5	6.0E+11	-
Euro-6	1-Sep-2014	1-Sep-2015	4.5	4.5	6.0E+11	6.0E+12
Euro-6c	1-Sep-2017	1-Sep-2018	4.5	4.5	6.0E+11	6.0E+11

Road traffic is one of the main contributors to air pollution. Since vehicle drive mainly where people dwell, their contribution to human exposure is even larger. For example, modern diesel and gasoline vehicles should have low PM emissions (see Table 1) but during their life time these PM emissions may increase for several reasons. Especially the introduction of specific technologies such as particulate filters (DPF or GPF) or direct fuel injection (GDI) substantially influence the real world PM emissions. Furthermore their technical status may deteriorate and this could increase the PM emissions of these vehicles.

Commissioned by the Dutch Ministry of Infrastructure and the Environment, since 1987 TNO regularly performs test programs to determine real-world emission performance of vehicles in the Netherlands. From 2012 onwards, special attention was paid to PM and PN emissions (Kadijk 2013, 2015, 2016a,b, 2017, Ligterink 2016). The main goal of the programs is to gain insight into trends in real-world emissions of light-duty vehicles under conditions relevant for the Dutch and European situations. These test data are the basis for the emission factors of Dutch road traffic.

On different moments in a lifetime of vehicles, emission tests must be performed and the actual emission levels are measured. These moments are:

1. Type approval (TA) of a new vehicle type carried by type approval authorities. The type-approval includes:
    i. Chassis dynamometer emission tests and from 2018 Real Driving Emission tests on a pre-model or prototype,
    ii. Durability tests of emission control devices, prior to type-approval, e.g., on an aging bench.
    iii. Conformity of production (CoP) tests of new vehicles, sampling the factory output.
    iv. Smoke emission test on a single engine
    v. In Service Conformity (ISC) by the manufacturer of a limited number of in-use vehicles with a maximum mileage of 100,000 km. Chassis dynamometer tests as well as Real Driving Emission (RDE) tests on the road are to be carried out for new vehicle models from September 2017.
2. Dutch national Periodic Technical Inspections (PTI) for all vehicles, mostly every two years starting at the vehicle age of 4 years carried out by PTI service stations or workshops. This is part of the national implementation of the road worthiness requirements.
3. Road Side Inspections (RSI) at random times carried out by national authorities. This focusses on illegal activities such as DPF removal and SCR tampering, on top of tax evasion, tachograph tampering, weight exceedances, road worthiness, etc..
4. Investigations by the Type Approval authority for prosecution on defeat devices. This had not led to a legal challenge so far.
5. Market Surveillance by the inspection authority (ILentT) from 2020 onwards. For L-cat (light) vehicles such requirement already existed, but no L-cat vehicle was ever tested by the Dutch inspection authority.
6. Granting Type Approval Authority, in the Netherlands: the RDW, has to perform independent ISC emission tests from 2020 onward.

Regarding Diesel PM, PN and smoke emissions in TA, ISC and PTI tests, there are a number of interlinking aspects. In type approval and ISC tests the PM and PN emission of each <u>vehicle</u> type is measured on a chassis dynamometer. The smoke emissions of an <u>engine</u> are determined in full load and free acceleration type approval tests. This free acceleration smoke test is also applied in PTIs. Unfortunately, the operating conditions of a free acceleration test are not representative for real-world operation and the smoke emission limit values for vehicles with a DPF are relatively high (Kadijk 2017), which could result in false positives.

In Figure 1 a picture of the ISC and PTI test regime is shown. Although the ISC PN limit values are quite strict, they are only applicable up to 100,000 km. Mostly at a vehicle age of 4 years the PTI test regime starts. The PTI smoke emission limit values are not strict ($< 0.7\ m^{-1}$) and not well related to real world PM emissions; Consequently the real-world emissions of older vehicles can be substantial. (Ligterink, 2016)

In the future monitoring programs (Mensch 2017) and periodic technical inspections (PTI) may not have the same function as the current legislation. If high emissions are observed for a vehicle, or vehicle model, in monitoring programs it might not be a priori clear if it is a road-worthiness issue, tampering, or has to be taken up in the in-service conformity.

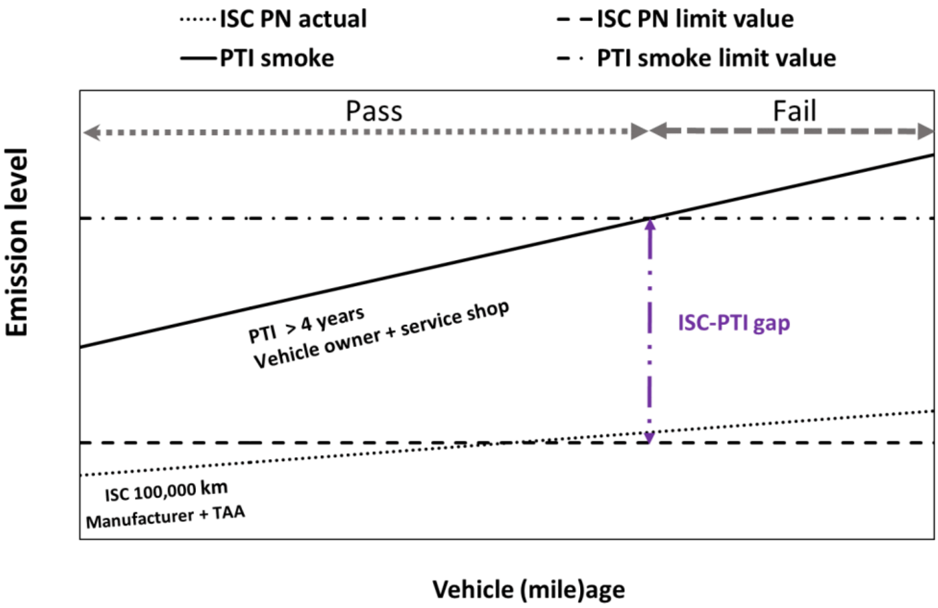

Figure 1: Example of the life time emission behavior of a diesel vehicle and different legislative instruments. The ISC-PTI gap may result in relative high average real world PM emissions of older vehicles.

Relevance of emissions of vehicles with high mileages

Modern Dutch passenger vehicles are on average more than 15 years on the road and often run more than 250,000 km. Many of the older vehicles have more urban usage than the average vehicle. Therefore, as to total annual mileage decreases, the urban mileage does not increase significantly. See Figure 2. (Ligterink 2017)

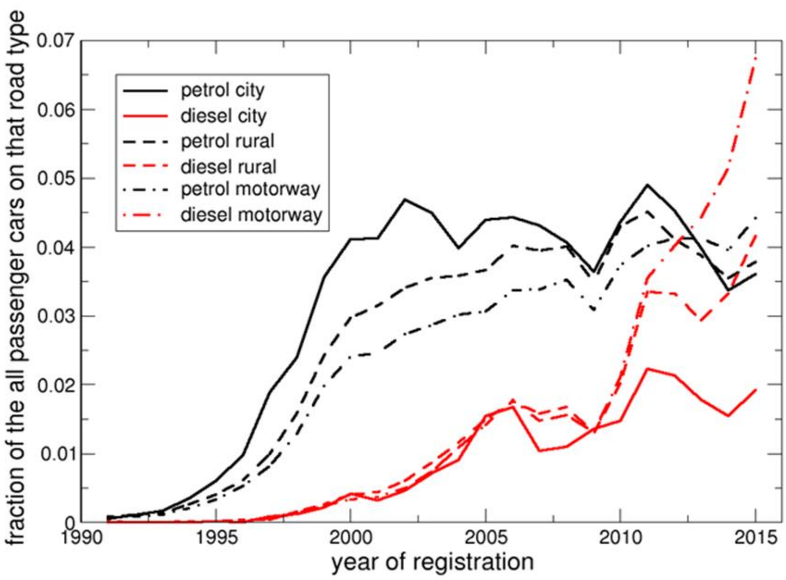

Figure 2: A measurement program collecting data from multiple locations in the Netherlands autumn 2015 show that gasoline vehicles with ages up to 18 years all have similar urban presence.

However, In Service Conformity (ISC) requirements of even the most modern vehicles only control the emission performance up to 100,000 km and durability is defined up to 160,000 km. Vehicles with high mileages contribute significantly to the total emission of Dutch road vehicles. In first test programmes of diesel vehicles with high mileages removed or bad functioning DPFs were detected. Moreover, for gasoline vehicles high NO_x emissions were detected. Maintenance and detecting malfunctions seem critical in retaining low emissions throughout the vehicle life. A typical modern vehicle covers in its lifetime at least double the distance specified in the type-approval requirements. The second half of the vehicle's lifetime is a shared responsibility among owner, manufacturer, road authority, inspection authority and the garage services.

Likewise, the group of older diesel vehicles, typically before 2007, which are not equipped with the DPF, are a major contributor to the Elemental Carbon (EC) emissions in the Netherlands. The rapid decrease of the number of older vehicles is cited as one of the main causes of the rapid reduction of traffic-related EC concentrations in the Netherlands since 2013.

Chassis dynamometer and on-road tests older gasoline vehicles

Older gasoline vehicles are assumed to be a major part in the exhaust particulate matter in the next decade, with the phasing out of diesel vehicles without DPF. It was unclear whether the high mileage of these vehicles, and, for example, higher oil consumption, would lead to higher particulate matter emissions, than below 100,000 km. In order to investigate this aspect and other possible issues, the gasoline vehicles were tested mainly on the chassis dynamometer, since this is still the only accurate method to determine the mass of the particulate matter emissions on a filter, in the range of 0-10 mg/km. From the first initial investigation of 3 vehicles, problems with NO_x emissions were observed, while particulate matter emissions were low. Another 3 vehicles did not lead to a conclusion. At the current level of 12 older gasoline vehicles tested (Kadijk 2018) it can only be concluded that a few vehicles with malfunctions have a major impact on the average NOx emissions. If a gasoline vehicle operates slightly lean, the emissions are quickly tenfold higher, above 1 g/km NO_x.

In 2017 and 2018 in total twelve Euro 2, 3, 4 and 5 gasoline vehicles with mileages between 155,000 and 254,000 km were tested on a chassis dynamometer in a laboratory (Kadijk 2018). These tests consisted of CADC tests at an ambient temperature of 15 °C, with a real-world road load and test mass. The NOx emissions varied from 17 to 1234 mg/km, see Figure 1, while all high emitters passed the OBD and four-gas test in the Periodic Technical Inspection (PTI). CO, PM and THC emissions were mostly at regular ISC levels. The Kia Picanto had a new exhaust line fitted, which may have caused additional PM emissions above the norm.

Table 2: Measurement results of 12 older gasoline vehicles on the CADC test.

	Euro Class	CO		THC		NO_x		PM	
		[mg/km]	CF	[mg/km]	CF	[mg/km]	CF	[mg/km]	CF
Citroën Xsara	3	719	0.3	8	0.0	39	0.3	0.1	0.0
Toyota Aygo	5	4135	4.1	25	0.3	17	0.3	1.1	0.2
Ford Focus	3	2476	1.1	97	0.5	254	1.7	2.3	0.5
VW Polo	4	2500	2.5	53	0.5	96	1.2	1.5	0.3
Opel Corsa1	4	724	0.7	23	0.2	375	4.7	3.9	0.8
Fiat Punto 1	4	5133	5.1	138	1.4	1234	15.4	3.7	0.7
Fiat Punto 2*	4	2317	2.3	25	0.3	30	0.4	3.5	0.7
Opel Corsa 2*	4	6187	6.2	86	0.9	275	3.4	3.6	0.7
Renault Megane Scenic*	4	1028	1.0	16	0.2	17	0.2	2.8	0.6
BMW 325i*	4	2021	2.0	130	1.3	1059	13.2	4.4	0.9
Kia Picanto*	3	6545	2.8	29	0.1	18	0.1	9.1	1.8
Volkswagen Golf*	2	1098	0.5	88	-	172	-	3.5	0.7

The high emissions are not correlated with a particular brand or model, nor with the emission class, Euro-2 to Euro-5, age, and specific high mileages. Since the problems could also occur in a Euro-5 vehicle, with the same technology, it is expected that this problem may affect the air-quality until 2030, since Euro-5 vehicles are likely to be present on Dutch road until then. Pending further investigation it is assumed that the average NO_x emissions increase to around 300 mg/km, based on 1-in-6 vehicles developing undetected malfunctions of the aftertreatment system (three-way catalysts and lambda controller). The Dutch government has requested further investigation of this problem, and the possible measures to reduce its severity. A dedicated emission test as part of the period inspection is one of the options.

Periodic Technical Inspection (PTI) tests for detecting high emitting vehicles

From 2015 to 2017 TNO tested 355 Euro 5 and 6 in-use diesel passenger cars and light commercial vehicles with a Diesel Particulate Filter (DPF) in a new PTI Particulate Number (PTI-PN) test at low idle speed (Kadijk 2015, 2016a, 2016b, 2017). High PTI-PN emissions occurred in 21 of the 355 vehicles. A draft PTI-PN test procedure with a dedicated specification of a PTI-PN-tester (related to PMP protocol for the PN standard), an emission test at low idle speed and PTI-PN limit values were developed.

In 2016 investigations of diesel vehicles with stationary tests found 5% to 7% of vehicles with increased particle number emissions, in a large range of values, compared to the very low baseline of properly functioning DPF technologies. In part this could be the result of filter removal, but in the cases it was investigated further, the increased particulate matter emissions were linked mainly to deterioration, i.e., cracked filters. This problem was not detected in maintenance and inspection. The current OBD, maintenance schedule, and road worthiness test do address this problem. A new test method is therefore required to detect elevated particulate matter emissions in vehicle inspection.

In 2018 the prevalence of filter removal leading to a largest increase in particulate matter emissions was investigate with garage workshop visits (Staps 2018). In total 89 car workshops are visited in the Netherlands, 83 workshops (93.3%) were cooperative with the research. However, six workshops (6.7%) were not willing to cooperate. According to the researcher these companies acted strange and they seemed threatened by the research. In the interview, 32 workshops (38.6%) indicated that they know customers who have removed the DPF. Together they know 212 customers with a removed DPF, an average of 2.5 customers per workshop. Within the research 86 workshops are approached, which represent the maintenance of 27.650 diesel vehicles yearly. This represents 1.05% of the total Dutch market of diesel vehicles. Within this diesel passenger and light commercial vehicles in 1.2% the DPF filter is removed. Given the uncertainties in the study, a lower estimate on 1.5% filter removal is assumed. This share represents a total 20,284 vehicles with a removed DPF in the full market. High costs on the filter replacement (an average of € 1200) or filter cleaning motivates most costumers to remove the DPF. The fraction of vehicles with removed filters may increase as the age of DPF equipped vehicles increases. On the other hand, DPF technology may mature after the initial technology from 2000-2008, reducing the malfunctions and maintenance issues.

In 2018 first attempts for a PTI-NOx emission test method for gasoline vehicles were explored but need to be elaborated in more detail (Kadijk 2018).

PM emissions of vehicles are strongly dependent on the applied technology. In Figure 3 the exhaust particulate emissions (EC and non-EC) from Dutch diesel and gasoline passenger cars in urban traffic with standard traffic flow are shown. Gasoline vehicles with direct fuel injection have little PM emissions, but these emissions are somewhat higher than the typical PM emission of diesel vehicles with a particulate filter. Wall flow diesel particulate filters (DPFs) are a very effective way to reduce emissions of soot particles in the exhaust gases. DPFs reduce the real-world PM emissions of light-duty vehicles with diesel engines strongly to an average of 1-2 mg/km, including the emissions associated with regeneration events. It is however known that DPFs are quite frequently removed if there are problems with DPF regeneration. Removal and tampering or manipulation of the engine software is more economical than a DPF replacement. The actual PM emission of such vehicles increase with a factor 25 to 100. Currently, there are no reasonable accurate tests to assess the presence or functionality of DPFs during periodic technical inspections. The current test that is used for periodic inspection of vehicles with diesel engines, the free acceleration smoke emission test, has a lack of sensitivity and it does not correlate with real world PM or PN emissions (Kadijk 2016b, 2017). Furthermore, the current limit values used for diesel smoke, can even be met without a particulate filter. Table 3 shows an overview of PM and PN emissions and risk of increased PM and PN emissions of gasoline and diesel vehicles.

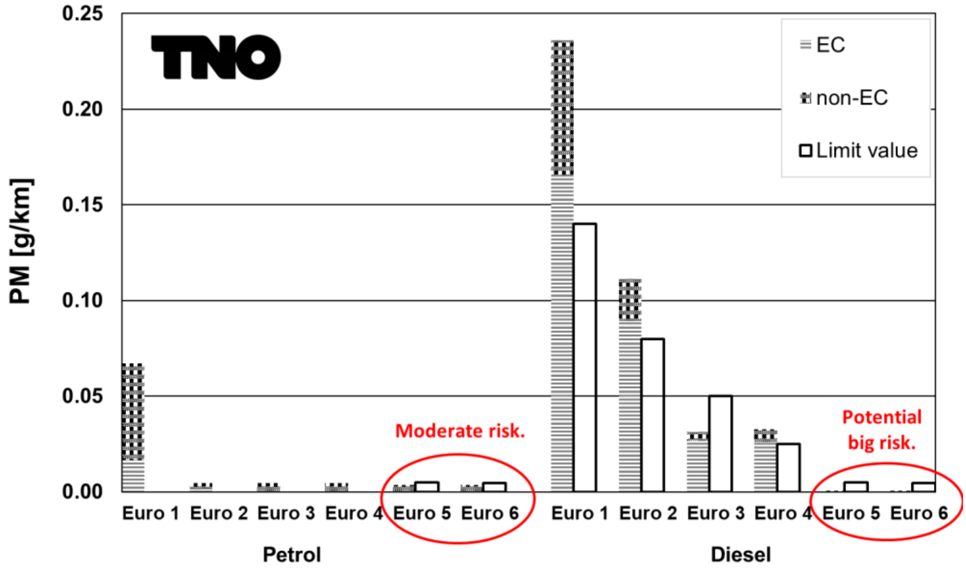

Figure 3: Exhaust particulate emissions (EC and non-EC) from diesel and gasoline passenger cars in urban traffic with standard traffic flow (no congestion). Due to technical failures or manipulation the PM emission of Euro 5&6 vehicles may be higher.

Table 3: PM/PN emissions and risk of increased PM/PN emissions

Field	Emission level Gasoline	Risk Gasoline	Emission level Diesel	Risk Diesel
Type approval	++	++	++	++
In Service Conformity	++	++	++	++
Real world emissions (RDE)	+	-	+	-
Durability	+/-	-	-	- -
Periodic Technical Inspection	n.a.	n.a.	-	- -
Road side inspections	n.a.	n.a.	-	-
Manipulation	-	+/-	- -	- -

++ very low risk, + low risk, +/- some risk, - reasonable risk, - - high risk

To be able to determine the trends of real world particulate emissions and to asses for possible risks on elevated emissions during the useful life of a vehicle, data was collected of several studies that were performed between 2013 and 2017 (Kadijk 2013, 2015, 2016a,b, 2017, Ligterink 2016) for which the particulate emissions of more than 500 diesel and gasoline passenger cars and light-duty vehicles were tested. The data comes from several types of PM and PN emission tests.

The following tests were performed:

- Chassis dynamometer emission tests according to UNECE R83.
- The EC fractions of the PM of the GDI vehicles were chemically analyzed.
- Smoke emission test for diesel engines according to UNECE R24 of 1958 & 72/306/EEC.
- Free acceleration and PN emission tests at idle speeds for Periodic Technical Inspection (PTI). PN test were done (also with cracked DPFs) with different (handheld) PN-testers which were correlated with the PMP-PN test protocol.

On the basis of the test program a simplified PN measurement standard, compared to the PMP-like protocol, is developed to be the basis of PTI and inspection authority test. It must be noted that a PN-based method is designed to establish the functioning of DPF technology, the connection with PM and air-quality remains tenuous, as particle numbers evolve over time subject to ambient conditions.

Emission compliance over the lifespan of a vehicle

Although Euro 6d real driving emission (RDE) legislation improve real world emissions these vehicles still have limited ISC (up to 100,000 km) and durability requirements (up to 160,000 km) (Mensch 2017). The current OBD and PTI tests are very limited or not suitable for detection of high emitters. Manufacturers, governments, service providers and vehicle owners have shared responsibility for robust vehicle emission performance over the lifetime of a vehicle. Therefore, a more integrated approach of ISC, OBD and PTI in post Euro 6 legislation is needed to improve emissions over the full lifespan.

If the 100,000 km (based on ISC criteria) or 160,000 km (based on durability) criteria, seems to be the proper guarantee date of emission control technology, such as DPFs, three-way catalyst, or lambda sensors that control the operation, it would be proper to insist on replacement of such parts. In a number of cases it is now found that the mileage over 160,000 km is no longer anybody's responsibility. The same as spark plugs, drivebelts, brake pads, and tyres, emission control technology may have wearable parts, which need to be replaced. Such replacements are part of proper maintenance. A PTI test should only be needed to ensure proper maintenance.

Potential ways to improve emission compliance

Current measures for improvement of the emission performance of vehicles are mainly addressed to governments and manufacturers. It is well known that users can have a major impact on vehicle emissions. TNO explores new projects with direct communication to groups of vehicle owners with the aim to improve the fuel consumption, emissions, use and maintenance of vehicles by sharing dedicated knowledge of vehicle emissions and showing best practices to vehicle owners. The H2020 uCARe project, starting May 2019, is dedicated to informing and helping car owners.

Eventually, after 2025, post-Euro-6/VI legislation should cover these aspects. It cannot be expected that manufacturers are alone responsible for the environmental performance. Currently, if there is unauthorised repair, replacement, an unattended MIL warning, etc. the manufacturer no longer takes responsibility for the ISC of the vehicle. This means many vehicles are only at the level of road worthiness, and the consequences of failing any of the requirements for the ISC program are not known. Very likely independent parties will have trouble finding vehicles fit for ISC testing.

Eventually, anybody should be able to check the maintenance state of the vehicle, so authorities can follow-up on different issues, such as illegal adaptions or substandard service. Before this ideal situation is reached, there will be many years of vehicles on the road with a unknown emission performance.

Effectiveness of PTI procedures

Effectiveness of the current In Service Conformity protocol:
The current ISC protocol is not very effective in solving a problem with a substantial rate of faulty vehicles. The procedure is designed to fail a vehicle model if 40% or more develop problems. The malfunctioning should appear within 100,000 km and despite good maintenance and moderate use. If, for example only a 25% of the vehicles develop problems, there is virtually no need for improvement of maintenance procedure, or the replacement of a defective part from the perspective of the ISC protocol. Such problems have been observed with inferior technology DPFs.

Improved PTI test procedure for diesel vehicles with DPF:
A draft PTI test procedure was developed for the detection of removed or broken DPF in a rather simple test procedure which constitutes of an idle test at which particle number concentrations are measured (Kadijk 2017). The procedure is meant to check for problems that concern (highly) elevated PM/PN emissions.

The current PTI smoke emission test procedure for diesel vehicles is outdated because the sensitivity of the opacimeter is too low; small and normal DPF failures and even a removed DPF cannot be detected. An improved PTI test procedure with relatively simple PN-test test equipment was investigated in cooperation with equipment manufacturers. A simple test performed at low idle speed with an appropriate PN limit value (i.e., 250.000 #/cm3) seems to be a good candidate to detect removed or broken DPFs. The PN emission at low idle speed has a good correlation with the regulated PN emissions in NEDC tests, although more tests are recommended to support this. Current mobile PN-testers are accurate but too expensive for PTI workshops. A new draft specification for a simplified low cost PTI-PN-tester for diesel vehicles is proposed (Kadijk, 2017) and has been developed by the Netherlands Metrological Institute (NMi). After standardization of this new PTI-PN-tester a final PTI test procedure may be built and implemented as a Type II emission test in UNECE R83 or WLTP regulations. However, the PTI-PN procedure does not cover the performance of the NO_x aftertreatment systems (LNT or SCR). Due to the very specific NO_x reduction technologies a dedicated PTI test procedure would be needed which can preferably also be performed at low idle speed.

The potential increase of PM emissions of older gasoline vehicles with GDI engines is expected to be moderate and can be well monitored in improved ISC test programmes. In case of GDI vehicles with a particulate filter (GPF) a dedicated PTI-PN test might be an option. For this specific PTI test of gasoline vehicles the development of a dedicated PTI-PN tester which can handle exhaust gas with higher water concentrations seems to be needed.

Conclusions

Now the real-world, on-road emissions of new vehicles seem to be controlled by effective RDE legislation. The next step is to ensure these emissions remain at a low level over the lifetime of the vehicle. Investigations by TNO so far have uncovered serious concerns with emission control technologies which were expected to be robust. Both the DPF as the three-way catalyst on older vehicles do not perform as well as may have been hoped.

The procedures to ensure proper performance of emission control in normal use, such as ISC and PTI, have serious flaws. It seems that the responsibility of the emission performance of vehicles in the second half of the vehicle’s life is not implemented. Consequently, a small fraction of vehicles with malfunctions or tampered with, cause the average emissions of these groups to double or more.

Better monitoring of PM, PN and NOx emissions of diesel and also gasoline vehicles seems necessary. This would need to include the following elements:

- Increase of the In Service Conformity (ISC) requirements above the current 100,000 km. A life time of 250,000 km or more seems more appropriate, especially for diesel engines.
- Introduction of a sufficiently accurate but simple PN test for the Period Technical Inspection (PTI), especially for diesel cars.
- Development and introduction of a sufficiently accurate but simple NO_x test for the Period Technical Inspection (PTI), especially for gasoline cars.
- A common definition of a vehicle in a proper environmental state, that connects all elements from type-approval to periodic inspection. This should place any emission test in a general context.

The combination of these elements is essential in addressing the different responsibilities in securing reasonable emissions during the life time of vehicles.

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