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TNO report

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Evaluation of the EU real-world PEMS test for heavy-duty vehicles

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Samenvatting

Sinds Euro VI van kracht is, moeten voor de certificering van een heavy-duty motor of voertuig (GVW>3.5t) verplicht praktijkemissietesten worden uitgevoerd. De invoering van dit type test heeft samen met enkele andere belangrijke aanpassingen in de EU emissiewetgeving geleid tot een forse afname van de gemiddelde NO_X emissies van zware bedrijfswagens. Voor een aantal toepassingen was het beeld echter nog wisselend, met name onder stadse rijcondities zijn de NO_X emissies regelmatig verhoogd [TNO, 2016], [TNO, 2018]. De praktijkemissietest is bedoeld om de NO_X emissies te controleren onder zogenaamde ‘normale gebruiksomstandigheden' van het voertuig. De test heeft grenscondities waarbuiten NO_X emissies niet worden gecontroleerd. Een analyse is uitgevoerd om te bepalen welke condities, die in Nederland typisch kunnen voorkomen, buiten de condities van de test vallen waardoor de NO_X emissies in principe ongecontroleerd blijven en er een risico is op verhoogde NO_X emissies. Nederland kan deze informatie gebruiken om in Brussel te pleiten voor verbetering van de praktijktestprocedure.

Belangrijkste conclusies en aanbevelingen
Voor de eerste generatie Euro VI bedrijfswagens schoot de praktijktest op een aantal punten nog tekort wat betreft het afdekken van de Nederlandse praktijkomstandigheden. Voor recent doorgemeten Euro VI vuilniswagens zijn dergelijke problemen al geconstateerd [TNO, 2018]. Ook voor bussen en alle andere toepassingen waar de gemiddelde snelheid laag is (congestie, stad) kunnen lokaal nog verhoogde NO_X emissies optreden. Op basis van eerder onderzoek [TNO, 2016] heeft Nederland al gepleit voor het verbeteren van de praktijktest. Een paar verbeteringen[1] zijn onlangs aangebracht en in 2019 wordt een volgende grote stap gezet. Daarmee wordt een groter deel van de rij-omstandigheden afgedekt dan voorheen, wat het risico op verhoogde NO_X emissies onder deze omstandigheden zou moeten terugdringen. Een deel van de rijomstandigheden en toepassingen wordt ook na de verbeteringen nog niet afgedekt. Dit komt doordat de evaluatiemethode periodes met hoge emissies buiten beschouwing laat. Hierdoor kunnen de NO_X emissies lokaal hoger zijn dan men op basis van de limiet voor de NO_X emissie zou verwachten.

Naast de praktijktest omvat de emissiewetgeving tal van andere maatregelen die bedoeld zijn om de emissies te reguleren. Een voorbeeld is de levensduureis. Deze dekt maar 50-60% af van de gemiddelde totale levensduur van een moderne dieselvrachtwagen. Andere voorbeelden zijn: primaire en toegelaten aanvullende emissiestrategieën, boorddiagnose, NO_x beperkingsmaatregelen. Het wordt aanbevolen om het geheel aan maatregelen en eisen te onderzoeken om te bepalen of er risico’s zijn die in de praktijk kunnen leiden tot verhoogde emissies. Ontwikkelingen in de VS (CARB) lijken aan te geven dat een forse verlaging van de NO_X uitstoot van zware bedrijfswagens met een geavanceerd emissiebeheerssysteem gemiddeld én over een breder inzetgebied (speciale toepassingen en speciale rij-omstandigheden als congestie) haalbaar is indien de bestendigheid tegen veroudering van het systeem is aangetoond.

[1] EC verordening nr. EC/2016/1718

Uitgebreide conclusies en aanbevelingen

Voor de huidige eisen, laatst geamendeerd door EC/2016/1718, ‘Step C’, vallen de volgende condities buiten de test, maar worden wel gezien als normale gebruikscondities voor Nederland:

- Normale inzet met hoge emissies. Vanwege de ’90-percentiel’ regel van de praktijktest worden 10% van de gemiddeldenvensters[2] buiten de testevaluatie gehouden.
- Rijden met een gemiddeld laag vermogen wordt buiten de testevaluatie gehouden door een onderste vermogensgrens te stellen voor de gemiddeldenvensters. Wanneer het vermogen lager is dan 20% van het maximale motorvermogen in een gemiddeldenvenster dan wordt het gemiddelden venster niet meegenomen bij de evaluatie van de praktijktest. Dit kan oplopen tot een maximum van 50% van alle gemiddeldenvensters van een test. Inzet met een gemiddeld laag motorvermogen is normaal voor sommige toepassingen als vuilniswagens, stadsbussen en distributievrachtwagens en kan zelfs voorkomen bij de vrachtwagens voor de lange afstand wanneer er sprake is van lage gewichtsbelading, files en druk stadsverkeer. Voor vuilniswagens bijvoorbeeld wordt hierdoor 50-90% van de normale inzet niet afgedekt.
- Het deel van de test waarin de koude start plaatsvindt en de motor opwarmt tot een koelwatertemperatuur van 70 graden Celsius wordt niet meegenomen in
- de evaluatie van de praktijktest, terwijl de koude start wel onderdeel is van de WHTC motortest voor de typegoedkeuring. Momenteel (Q1 en 2 van 2018) wordt onderzocht en besproken in de werkgroep in Brussel hoe de koude start moet worden meegenomen. Het doel is om de ‘koude start’ in 2020 in te voeren (‘Step E’).
- De toepassing van de hierboven genoemde regels leidt er toe dat de hoogste emissies buiten beschouwing worden gelaten bij het evalueren van de praktijktest.
- Tijdelijk verhoogde emissies worden uitgemiddeld in vensters die tot 1530 seconden kunnen duren. Emissies kunnen dus lokaal verhoogd zijn en wegvallen in de gemiddelden. In hoeverre dit aan de orde is, is nog niet onderzocht.
- De testrit die uit moet worden gevoerd is niet altijd representatief voor de inzet van het voertuig. Speciale voertuigen moeten de voorgeschreven N2 (lichte vrachtwagen), N3 (zware vrachtwagens), M3 (bussen) ritten rijden terwijl deze niet de normale gebruiksomstandigheden representeren, zoals het binnenhalen van huisvuil voor vuilniswagens, het stoppen bij een bushalte voor bussen, straatvegen voor straatveegmachines, goederen bezorging voor distributievoertuigen enzovoort. Ook speciale voertuigconfiguraties hoeven niet te worden getest, bijvoorbeeld voor NL relevant: LZV’s.
- De grenzen voor de gemiddelde snelheid over het stadsdeel van de test (15-30 km/h) dekken typische inzet niet af. Voorbeelden zijn vuilniswagens (7-20 km/h) en drukke stadslijnen voor bussen (10-15 km/h).

[2] Gemiddeldenvenster: een schuivend venster met een zekere tijdsduur waarover de emissies worden gemiddeld. Hoe lang het venster duurt, wordt bepaald door hoe lang het duurt voordat de motor een zekere hoeveelheid arbeid heeft geproduceerd, vergelijkbaar met de WHTC motortest. Bij een laag vermogen duurt dat langer dan bij een hoog vermogen. Er geldt een onderste vermogensgrens (power threshold) waardoor de tijdsduur van een venster impliciet wordt gemaximeerd en vensters met een gemiddeld laag vermogen, lager dan de ‘power threshold’ de onderste vermogensgrens buiten beschouwing worden gelaten bij de evaluatie van de praktijktest.

- De emissie van deeltjesaantallen wordt nog niet gecontroleerd in de praktijktest, terwijl dit voor de typegoedkeuringstest aan een motor wel moet gebeuren. Momenteel loopt een proefprogramma waarin de instrumenten en procedures om de deeltjesaantallenemissie te meten worden uitgeprobeerd met als doel de procedure op te nemen in de praktijktest in te voeren met 'Step E'.

Voor 'step D', die van kracht gaat op 1 september 2019 voor alle voertuigen, geldt dat de 'power threshold', de onderste vermogensgrens voor gemiddeldenvensters, verlaagd wordt van 20 (tot 15%) naar 10%. Dit houdt in dat gemiddeldenvensters met een lager vermogen moeten worden meegenomen bij evaluatie van de praktijktest. Daarmee wordt een groter bereik van het motorvermogen afgedekt door de praktijktest. Sommige voertuigtypen zoals vuilniswagens rijden echter regelmatig met nog lagere gemiddelde motorvermogens.

Belangrijke condities die wel door de praktijktest worden afgedekt:
- Een verplicht gemiddeldenvenster met alleen rijden in stad zodat zeker is gesteld dat emissies minimaal voor één venster met alleen rijden in de stad wordt gecontroleerd (sinds verordening nr. EC/2016/1718). De minimum eis van één verplicht venster met 'rijden in stad' betekent dat er nog steeds vensters met 'rijden in de stad' buiten de evaluatie kunnen vallen.
- De meeste omgevingstemperaturen en hoogtes die in Nederland voorkomen.
- Belading. Sinds verordening nr. EC/2016/1718 geldt dat beladingsgraden van 10 tot 100% worden gezien als normale gebruikscondities en daarmee wordt indirect vereist dat bij deze beladingsgraden de emissies moeten voldoen aan de eisen voor de conformiteit van in gebruik zijnde voertuigen. Voor de typegoedkeuringstest geldt overigens een beladingsgraad van 50 tot 60%.

Naast de praktijktesten zijn andere maatregelen van kracht om de emissies te beteugelen.
Dit zijn:
- De motorcertificeringstesten, met name de WHTC en WHSC test.
- Levensduureisen.
- Aanvullende en primaire emissiestrategieën.
- NO_x beheersmaatregelen.
- Emissies buiten de cyclus.
- Boorddiagnosesysteem.
- Conformiteit tijdens het gebruik.

Het is belangrijk dat deze maatregelen elkaar aanvullen met het oog op het waarborgen van lage praktijkemissies en om zeker te stellen dat er geen tekortkomingen zijn die door het geheel aan maatregelen niet worden afgedekt. Een risicoanalyse van het geheel aan maatregelen in de emissiewetgeving voor zware bedrijfswagens zou een beter zicht geven op welke condities al dan niet worden afgedekt. Samen met een analyse van de emissietrends van zware bedrijfswagens in de praktijk wordt een beeld verkregen of de emissiewetgeving voor deze categorie effectief is in het beteugelen van de hoge emissies.
Voor de zware categorie bedrijfswagens is nog niet bekend of en hoe vaak deze rijden onder condities die niet worden afgedekt door de praktijktestprocedures en in het bijzonder geldt dit voor de mogelijke situaties met een gemiddeld laag vermogen. Het testen van deze voertuigen tijdens daadwerkelijk gebruik geeft meer inzicht in de praktijksituatie voor de gegeven categorie.

Ontwikkelingen buiten de EU

In de Verenigde Staten wordt in opdracht van CARB (California Air Resources Board) onderzoek gedaan naar technische maatregelen om de NO_X emissie van vrachtwagenmotoren verder terug te dringen, ook onder de meer uitdagende condities zoals rijden met een laag motorvermogen. De CARB overweegt het verlagen van de US2010 grenswaarden waarbij wordt gekeken naar drie scenario's waarbij een verlaging met -90% voor de limiet voor de NO_X emissies de strengste is. Ook worden zwaardere testeisen overwogen. Om de lage NO_X emissie te kunnen halen zijn passieve en actieve thermische maatregelen nodig aan het emissiebeheerssysteem, samen met een toename van het conversierendement van de SCR katalysator en een avanceerde doseerstrategie. De toename van de kosten boven op de bestaande kosten voor een SCR systeem lijkt relatief laag te zijn. Een uitgebreid onderzoek dat zich onder meer richt op de levensduur is nog niet afgerond. In China wordt voor de volgende aanscherping van de emissiewetgeving (China VI) overwogen om de NO_X uitstoot verplicht op afstand te monitoren. De ontwikkelingen in het CARB-SWRI pilot programma lijken aan te geven dat met een geavanceerd emissiebeheersingssysteem voor NO_X de grenzen van de testcondities voor de praktijktest verder kunnen worden opgerekt. Dan zou een groter deel van de representatieve rijomstandigheden worden afgedekt wat zou leiden tot lagere praktijk NO_X emissies.

Summary

Since Euro VI, a real-world emissions test with PEMS is a mandatory part of the EU certification process of heavy-duty diesel engines and vehicles (GVW >3.5t). Together with some other major changes in the emissions legislation this has led to a large decrease of the average NO_X emissions of heavy-duty vehicles.
The real-world emissions test is meant to control NO_X emissions under ‘normal conditions of use’ but has boundary conditions outside which NO_X emissions are not tested and therefore these conditions may not be controlled by the legislation. A risk-based assessment was performed to determine what situations, that typically occur in the Netherlands, are not controlled by the on-road emissions test for heavy-duty engines and vehicles and which may potentially lead to elevated NO_X emissions under those conditions. The Netherlands can use the insights to advocate better procedures for the European real-world emissions test for heavy-duty vehicles.

Main conclusions and recommendations
For the first generation of Euro VI vehicles the real-world test fell short in covering some Dutch representative driving conditions. For Euro VI refuse collection vehicles such problems have already been observed [TNO, 2018]. For other applications, such as city buses, where driving speed is low on average (congestion) emissions can be elevated locally. Based on previous investigation the Netherlands plead for improvement of the test procedure. Some improvements have already been implemented[3] and in 2019 another important change will enter into force.
With these improvements, a larger share of real-world driving conditions is covered than before. This should reduce the risk of elevated NO_X emission under these conditions. Next to these improvements still some conditions are not well-covered. The cause is that the evaluation method still excludes periods with high emissions. Because of this NO_X emissions may locally be higher than one might expect based on the limits.

Besides the real world test, there is a range of other measures that are meant to control NO_X emissions. Examples are: durability, base and auxiliary emission strategies, on-board diagnostics, NO_X measures. It is recommended to investigate this whole package of measures to determine if there are any risks on elevated NO_x emissions occurring during the lifetime of a vehicle.
Developments in the US (CARB) seem to indicate that a further, on average large, reduction of the NO_X emissions is achievable with an advanced aftertreatment system and over a wider range of driving conditions than currently covered by the EU real-world test.

[3] EC regulation nr. EC/2016/1718

For the current requirements, last amended by EC/2016/1718, ‘Step C’, the following conditions are not part of the scope of test, but are considered normal conditions
of use in the Netherlands:

- Normal operation with high emissions. Due to the ‘90-percentile rule’ of the real world test, 10 % of the moving averaging windows[4] are excluded from the pass-fail evaluation.
- Low power operation, with an average engine power lower than 20% (to 15%) is excluded from the pass-fail evaluation due to the ‘power threshold’. Operation with low engine power is typical for some applications such as refuse collection vehicles, buses and distribution trucks and it may also occur for others such as the heavy goods vehicles were traffic jams, low payload, and city operation leads to low average power. This constitutes 50 to 90% of normal operation of a group of tested RCV’s and buses.
- Cold start is normal operation for heavy-duty vehicles. Cold start, and subsequent driving until the coolant temperature reached 70 degrees Celsius, is excluded from the evaluation. How cold start is to be included is discussed at the moment (2018) and inclusion of the cold start is scheduled for 2020 with ‘step E’.
- In practice the successive application of the above mentioned rules of evaluation result in the exclusion of the majority of the data with the poorest emission performance.
- Temporal changes in emissions are averaged out over the period of a moving averaging window. Local emission can therefore still be high and underestimated in air-quality assessments. The significance has not been investigated and is not included in current emissions factors.
- The prescribed test trip does not always represent normal operation for a vehicle. For instance, special vehicles need to drive the well-specified routes (N2, N3, …) which do not represent the typical operation of the special vehicle such as bus operation with stops, garbage collection, street cleaning, delivery of parcels and goods. Also special or alternative vehicle configurations of standard vehicles do not need to be tested (e.g. LZV, 50-60 ton GVW vehicles).
- The boundaries for average speed of the urban trip (15-30 km/h) do not cover operation of garbage trucks (7-20 km/h) and operation over heavy bus lines (10-15 km/h).
- Particle number emissions are not tested, while these emissions are tested at the type approval test of the engine. A pilot programme is running (2017-2018) in which the measurement equipment and procedures are assessed which are necessary for the measurement of real-world PN emissions, probably implemented with ‘Step E’.

For step ‘D’, which accounts for type approvals for all new vehicle as of 1 September 2019, the power threshold is lowered from 20% (up to 15%) to 10% of the maximum rated engine power. This means that moving windows with a lower average power need to be taken into account for the pass-fail evaluation. Consequently, a larger part of the power range of engine operation is covered by

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[4] A moving averaging window (MAW) is a period of time over which emissions are averaged and that has a duration that depends on the average power of the engine in that period. The duration is determined by a fixed amount of reference work or alternatively CO_2 mass that has to be produced. The power threshold maximizes the duration of the windows. The window becomes shorter at a high average power and longer at lower average power. Windows with a low power below the threshold (long duration) ae not taken into account.

this measure. Still, some types of vehicles such as refuse collection vehicles often operate at lower power levels than 10%.

Important conditions which are covered:

- One moving averaging window with urban driving is mandatory part of the pass-fail evaluation, since the immediate entry into force of 2016/1718. This minimum requirement however means that still windows with urban only operation may be excluded from data-evaluation by the 90-% rule or the power threshold rule.
- Typical Dutch ambient conditions and altitudes are mostly within the real-world test boundaries.
- Payload. Since 2016/1718, the ‘normal conditions of use’ include payloads of 10 to 100%, which means vehicles needs to be compliant regarding in-service conformity in this payload range. For the type approval test the payload needs to be in the range of 50-60%.

Next to the real-world emissions test, other measures are in place which are meant to control emissions during normal operation over the useful life of an engine/vehicle.
These measures are:
- Engine certification tests (WHTC, WHSC).
- Durability.
- Auxiliary Emissions Strategies/Base Emissions Strategies.
- NO_x control measures.
- Off-cycle emissions.
- On-board Diagnostics.
- Conformity of production.
- In-service conformity.

Important is how complementary these measures are, if they overlap or leave gaps not covered. A risk-based assessment into the whole legislation that controls NO_X tail pipe emissions of HDV would give a better view of what conditions are covered and which are not. Together, with an assessment of the real-world emissions trends of generations of HDV’s it would reveal whether or not current Euro VI legislation is effective in lowering NO_X emissions under all normal conditions of use in the Netherlands. For the heavy category of trucks it isn’t known how much these vehicles drive in low engine load conditions. Additional testing of this category in real operation in 2018 will extend the knowledge into how much these situations occur and what their contribution is to total, and local NO_X emissions.

Developments outside EU
Research in the US (CARB, SWRI) is investigating technical measures to further decrease the NO_X emissions of heavy-duty diesel vehicles, also under the low engine load conditions. Based on this, US CARB is considering a tightening of US2010 limits for which three levels are considered with the most stringent one of them is a decrease of the limit with -90%. To achieve such low NO_X emissions would require passive and active thermal strategies and an increase of the SCR efficiency by advanced dosing strategies and catalyst materials. The cost for such technology is estimated to be a relatively low add on cost compared to current technology.

An extensive assessment that includes durability testing has not finished at time of writing. For China VI real-time monitoring of NO_X emissions is considered.

The developments in the CARB-SWRI pilot programme seem to indicate that with an advanced system for NO_X abatement wider boundaries for the PEMS test are feasible. In this way more representative driving conditions would be covered, leading to a decrease of real-world tail-pipe NO_X emissions.

Contents

1 Introduction

1.1 Background

The tail-pipe emissions of vehicles and engines are regulated since 1970 by means of European type approval. The type approval uses test procedures to check the level of tail-pipe emissions of a range of noxious gases against a set of limits. The effectivity of these test procedures has been under discussion, as the emissions of NO_X (and NO_2 separately within NO_X) are regularly higher in the real-world than the level one might expect based on the formal limits. The most important cause is the narrow bandwidth of test conditions at which vehicles/engines are to be tested in an emissions testing laboratory and under which they have to comply to the requirements, while in the real-world the bandwidth of normal conditions of use if much larger. This happens while it is actually the main goal of the type approval legislation to achieve low emissions under normal conditions of use and not only under very specific laboratory test conditions.

That is why, for heavy-duty vehicles since 2014, a real-driving emissions test is a mandatory part of the European type approval and in-service conformity checking scheme. The real-word test needs to be performed at the first type approval and consecutively, a number of vehicles has to be tested in the real-world at different moments over their useful life, to check the conformity of the engine in-service. Aside from this real-world test requirement, a range of additional measures aim to support the legislation in order to achieve the so-needed low real world emission of NO_X.

The package of requirements and measures, including the real-driving test with Portable Emissions Measurement System, needs to make sure that real-word emissions are controlled under conditions that are representative for the Member States of the EU. For the Netherlands, it is very important that the driving conditions that occur at hot spots with air quality problems are included in the scope of the requirements as much as is technically feasible and against reasonable costs.

1.2 Goal

The goal is to evaluate how well the real-world test in HD emission legislation cover conditions that are considered normal for the Netherlands, and relevant for air-quality. Conditions outside the test boundaries are in principle not covered and under such conditions there is a risk that NO_X emissions may be elevated.

The following questions need to be answered:

- In how far do real-world emission tests of the EU emission legislation for HD engines and vehicles cover the Dutch situation. What conditions are considered normal operation and fall outside the boundaries of the test conditions.
  The following is taken into account:
  - the current status of the legislation (‘step C’, last registration until 31-12-2018),

  - scheduled future requirements (‘step D’, new types as of 1-9-2018) and
  - inclusion of the cold start in the pass-fail evaluation and particle number testing for PEMS.
- Is cycle beating real-world tests possible?
- Is a further tightening of the limits feasible with the current emission reduction technology?

1.3 Scope

The European emission legislation consists of an extended package of measures and requirements. This investigation aims at the part that is relevant for controlling emissions under real-driving conditions considered normal for the Netherlands. This is primarily the real-driving emissions test with PEMS (Portable Emissions Measurement System) that is to be performed for type approval and to check the in-service conformity. Other measures with relevance for real-driving emissions (like NO_X control measures, measures taken against defeat devices, OBD and OCE (in-use off-cycle Emissions), measures for durability and requirements regarding allowed auxiliary and base emissions strategies) have not been evaluated. Items that can impact NO_X emissions but that fall under responsibility of the user/owner will not be discussed. These items are for instance manipulation (shut off AdBlue dosing, dismounting a DPF/SCR system), inspection and maintenance, malfunctions. Tipping point for responsibility lies between in-service conformity and OBD on the hand of the manufacturer and proper maintenance, responding to possible malfunction indications (MIL) and periodic inspection on the side of the owner. In-service conformity testing is performed with vehicles properly maintained and with no malfunctions. Manufacturer is therefore not responsible for malfunctions caused by improper maintenance by the owner. However, on-board diagnostics should still detect emission related malfunctions and measures should be taken to prevent manipulation by the owner.

1.4 Approach

The approach is split up according to the three main research questions:

1. In how far do current and new real-driving emissions tests of the EU emission legislation for HD engines and vehicles cover the Dutch situation regarding real-world operation of HDV?
   a. What is the bandwidth of (test-) conditions for testing real-world emissions? What are the typical real-world driving conditions in the Netherlands?
   b. What are the boundaries? Typical examples are applications with low load driving, like buses, refuse collection vehicles and distribution vehicles.
   c. Compare those representative conditions of use with the test conditions and requirements so that any possible differences can be determined, i.e. whether or not there are real world situations which are still not or not well- covered in current emissions legislation.

2. Is cycle beating a real-world test possible?
   Evaluate the real-world test procedures to determine whether the test can be detected and the test can be beaten.

3. Would a further reduction of the current limits be achievable with available technology?
   Investigate if there are developments of measures that go beyond Euro VI outside the EU (U.S., China and Japan). What are the motives and has the technical feasibility been investigated. The approach should take account of the technical feasibility of emissions reduction systems to reduce NOx and in particular the operating windows of NOx reduction systems (SCR catalyst: catalyst temperature and AdBlue dosing temperature, EGR: engine load and engine temperature).

2 EU HD PEMS test and coverage of Dutch real-driving conditions

2.1 Overview of requirements

The EU emissions legislation for the certification of HDV consists of a few separate regulations and quite a number of supplements, see Annex 1.
Often the EU regulation refers to world harmonized regulations and procedures for heavy-duty engines and vehicles as defined in ECE Regulation 49.

Overview of most important regulations:
- ECE Regulation 49
- EU Type approval (EC) framework directive 2007/46
- (EC) Regulation No 595/2009
- (EC) Regulation No 582/2011 and amendments
- (EC) Regulation No 2016/1718: To date the latest amendment to (EC) No 582/2011. It contains improvements of the PEMS test and changed requirements for PEMS data evaluation (lower power threshold: entering into force 2019). Cold start and PN are discussed in the PEMS-HD working group and to be implemented.

In principle the EU legislation that deals with regulation of tail-pipe emissions of HDV covers a broad range of measures from type approval to road-side inspection, each with responsibilities for different parties, i.e. the manufacturer and the owner:

1. Type approval, conformity of production, in-service conformity, durability and on-board diagnostics (Regulation 595/2009 and 582/2011/EC and amendments), see Annex 1: manufacturer.
2. Roadworthiness: periodic and road-side inspection (Directive 2014/47/EU, Regulation 595/2009): owner.

2.2 On-road emissions testing under real-driving conditions with PEMS for type approval and in-service conformity

On-road emission tests with PEMS are to be performed for type approval and for in-service conformity over the useful life (see Table 3). The latter shall start after 18 months of first registration and be continued over the useful life. For the first demonstration at type approval, the engine type is tested in the most representative vehicle for that engine. For in-service conformity, demonstration tests are requested by the type approval authority to be performed in other types of vehicles the engine is mounted in.

[EC Regulation 582/2011] "…A manufacturer shall take technical measures such as to ensure that tail pipe emissions are effectively limited throughout the useful life under normal conditions of use. The conformity to be checked over the useful life and under normal conditions of use as specified in Annex II of Regulation No. 582/2011 (conformity of in-service engines and vehicles and PEMS testing)…"

The requirements for PEMS testing and the pass-fail evaluation effectively determine the 'normal conditions of use' under which tail-pipe emissions are to be effectively limited over the useful life. The requirements for PEMS testing, the pass-fail evaluation and the useful life over which vehicles are to be checked, are described in EC 582/2011 and amendments.

- EC 582/2011: contains the first set of requirements for PEMS testing and the pass fail evaluation for in-service conformity of Euro VI engines and vehicles (as of 31 December 2014).
- EC 2012/64: contains small set of amendments to the PEMS test procedure.
- EC 2016/1718: contains a large set of amendments to the PEMS test procedure (immediate entry into force after publication) and some adaptations to the pass-fail evaluation limits, entering into force 2019.

Table 1: Euro VI steps and applicable power threshold.

	PEMS test Power threshold	Reagent quality	NO_x OTL	PM OTL	IUPR	Additional OBD monitors	Implementation all vehicles	Last date of registration	Remarks
Step A	**20**	Phase in	Phase in 1.5	25	Phase in	N/A	31.12.2013	31.12.2016	
Step B	**20**	Phase in	Phase in 1.5	25	N/A	N/A	1.9.2015	30.12.2016	
Step C	**20**	General	General 1.2	25	General	Yes	31.12.2016	31.12.2018	
Step D	**10**	General	General 1.2	25	General	Yes	1.9.2019		
Step E	**10**						Expected date 2020		To be implemented: - Cold start - PEMS-PN testing - New AES requirements

Moving averaging window method

For the PEMS evaluation, for the gaseous emissions, a Moving Averaging Window (MAW) is applied to the second-by-second emissions data of a PEMS test trip.
For each window the average emission is calculated. The duration of each window can vary. The window is as large as the duration that is needed to produce the same amount of work as would have been produced over a type approval WHTC engine test. This means that the duration of a MAW is exactly 1800 seconds when the average power is the same as over a WHTC test cycle.
But at a lower average power the window becomes proportionally longer.
The window duration is limited. This duration is limited by means of the lower 'power threshold' which means that MAW with a low average power are excluded from the pass-fail evaluation.

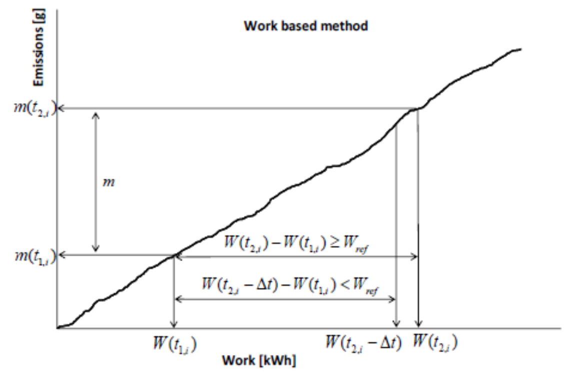

Figure 1: Principle of the Moving Averaging Window (Work Based).

Exclusion of Moving Averaging Windows from the pass-fail evaluation
Before the conformity factor is calculated for the MAW with the highest brake specific emissions, certain data and MAW are excluded from the evaluation:

- **First** the data which does not meet the applicable conditions is excluded. This is:
  - data obtained when the engine has a **coolant temperature below 70°C.**
  - data of **ambient temperature lower than -7 °C and higher than +38 °C**. The upper temperature threshold varies slightly with ambient pressure.
  - data with an **ambient pressure below 82.5 kPa** (associated with high altitude).
- **Then MAW with a low average power, below 20% of maximum engine power are excluded.** When there are less than 50% valid windows (windows that fulfill the criteria of power and coolant temperature) in a test, the threshold is lowered in steps of 1% to a minimum of 15% until there are sufficient valid windows. The test is void if there are less than 50% valid windows.
  The threshold will be lowered for step A, B and C from 20% (20…15%) to step D 10% in 2019.
- **Finally, 10-percentile of the MAW with the highest brake specific emissions are excluded.** These MAW are always excluded. This means that of the remaining 90% of valid MAW, the MAW with the highest brake specific emission determines the conformity factor.

Conformity Factor
Over each MAW the average brake specific emission in that window is divided by the applicable WHTC type approval limit. Some windows are not included in this evaluation. After exclusion of those MAW, the MAW with the highest specific emission (in g/kWh or g/kg CO_2) is the one that determines the conformity factor, i.e. the average specific emissions in that MAW divided by the WHTC limit value. This conformity factor is limited to 1.5.

Definition conformity factor CF: CF = e / L

e= specific emission in g/kWh of the selected valid window with the highest value,
L = limit value of the WHTC test in g/kWh.

This means that the MAW with the highest emissions, after exclusion of certain MAWs, may have an average specific emission of no more than 1.5 times higher than the limit of the WHTC engine test cycle. The Conformity Factor of 1.5 accounts for all regulated gaseous pollutants. So far, there are no provisions in the PEMS test for PM and/or PN. Possible inclusion of PN is discussed in the PEMS-HD working group.

Technical state of the vehicle
PEMS tests for in-service conformity are to be done in a test plan for tests over the useful life of the vehicle, with the vehicle in a proper state of maintenance, with no malfunctions and without emission related error codes stored in the ECU.
Any malfunctions need to be repaired before test. As such, the in-service conformity test only checks the vehicle, engine and emission control system when these are in a good condition without malfunctions. A wider assessment of emissions legislation would reveal how well this is working together with OBD requirements which are in place to diagnose and detect emission related malfunctions.

Sampling plan
A sample for one engine family needs to contain at least three test different vehicles. The number of test vehicles needs to be increased if one or more vehicles of the sample fail the PEMS test. A certain share of vehicles is allowed to not pass the real-world PEMS test.

Durability
Engine and vehicles need to fulfill the in-service conformity requirements over their useful life. The useful life differs per vehicle category. For N3 vehicles the useful life is 700.000km or 5 years, whichever is sooner. The actual lifetime of a HD tractor today is more than a million kilometers and lifetime extends beyond 5 years.
Also for the other categories lifetimes and lifetime mileages are expected to be higher. Control by means of in-service conformity is thus limited to about half of the real life time.

Table 2: Typical lifetime mileages for diesel engines.

Engine capacity [litre]	Life time mileage
4 to 5	~650.000 km
7 to 9	~ 850.00 km
9 to 13	~1.200.000 to 1.800.000 km

Table 3: Useful life per EU vehicle category.

Category	Useful life
M1, N1, M2	160000 km or 5 years
N2, N3 (<=16t), M3 class I, II <=7.5t	300000 km or 6 years
N3>16t, M3 class III >7.5 t	700000 km or 5 years

3 Real-driving of HDV in the Netherlands and coverage by the real-world PEMS test

For the on-road PEMS test procedure there is a range of requirements for the test trip and other driving conditions. In addition, there is a set of calculation rules that needs to be applied to the PEMS test data for the determination of the Conformity Factor (CF). These test requirements and calculation rules together determine the scope for which vehicles or engines have to be compliant, i.e., have a Conformity Factor lower than 1.5 for type approval and in-service conformity. Each requirement for the test procedure and calculation rule is examined to determine whether the typical range of normal driving conditions in the Netherlands is covered by the on-road PEMS test or not.

3.1 Data exclusion: Cold start

A cold start is relevant for emissions because usually an engine, that is colder than its normal operating temperature, may produce higher emissions from the engine, and an emission control system that is not at operating temperature or active does not effectively reduce those emissions. A cold start is not exactly defined.
In principle a cold start means a start of the engine after it was stopped for a period of hours and the engine and emission control systems have been cooling down since and stabilized to a level that depends on the ambient temperature at which the vehicle is parked.

In the new PEMS test a cold start is included. However, the cold start is not part of the pass-fail evaluation as data with an engine coolant lower than 70 °C is excluded from the evaluation. The coolant temperature of 70 °C shall be reached within 15 minutes after the engine start. For the new PEMS test, the cold start needs to be performed with a coolant temperature lower than 30 °C. The PEMS working group discusses in the first half of 2018 the possible inclusion of the cold start in the pass-fail evaluation with the amendment expected beginning 2019.
Several methods are possible and they are to be evaluated.

An evaluation of SEMS data, NO_X sensor, GPS and CAN data obtained from 10 vehicles over few weeks of real-world operation per vehicle, showed an average contribution of cold start emissions (ECT <70 °C) of 17% to the total emissions. The data was obtained under higher than average ambient temperatures (spring and summer in the Netherlands). The engine test does constitute cold start emissions. A cold started and a warm started WHTC engine test are weighted 10 and 90% respectively. This means that these emissions do account for achieving the emission limits. Not taking the cold start into account in the real-world test is an implicit relaxation of the limit.

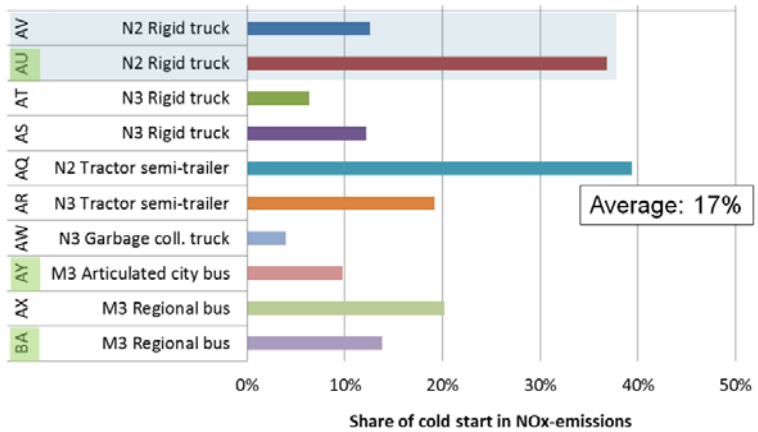

Figure 2: Percentage of the total NO_x emissions that can be attributed to cold start and warm up period of the engine and emission control systems, until a coolant temperature of 70 °C has been reached. Vehicles have been tested in daily operation.

Conclusion
The cold start and the warm up period are not covered in the current step “C” PEMS test, because data of engine coolant temperatures below 70 °C are excluded from the pass-fail evaluation. On the other hand, the cold start is included in the WHTC engine test. There, a cold started WHTC engine test has a 10% share in the combined WHTC test result and the engine start temperature is limited to the range of 20 to 30 °C. A main option is to include the cold start in the same manner as for the WHTC engine test; the cold start is to be performed with an engine coolant temperature between 20-30 °C and weighing the cold start (10%) in the final result of the pass-fail evaluation. Cold starts outside the 20-30 °C temperature range are not discussed at the moment. These starts are however common in the Netherlands. At a cold start, at low ambient temperatures which still is in the scope of a PEMS test, an auxiliary emission strategy may be active to protect the engine or after treatments system (low SCR temperature does not allow dosage of reagent for instance and EGR may need to be deactivated to protect the system from fouling).

3.2 Data exclusions: Ambient temperature, pressure and altitude

The regulation describes a temperature window for a PEMS test.

$266 < T <= -0{,}4514 \times (101{,}3 - pb) + 311$ [T in K]

For a moderate ambient pressure of 101,3 kPa this is a temperature window of:

-7 to 38 °C (@101,3kPa)

At a very low ambient temperature, usually below -11 °C, an SCR system with current technology is not able to operate because the reagent will freeze at the low temperature and it will clog the dosing system and catalyst. To prevent malfunctioning of the SCR system, a manufacturer may take measures to protect the system by shutting of the AdBlue dosing system at low temperatures below -7 °C.

From weather statistics it can be determined that ambient temperatures in the Netherlands are almost all of the times between -7 and 38 °C. Only a very small fraction of time temperatures fall below -7 or above 38 °C. This means that the largest portion of all driving of HDV in the Netherlands occurs within the temperature window of the PEMS test.

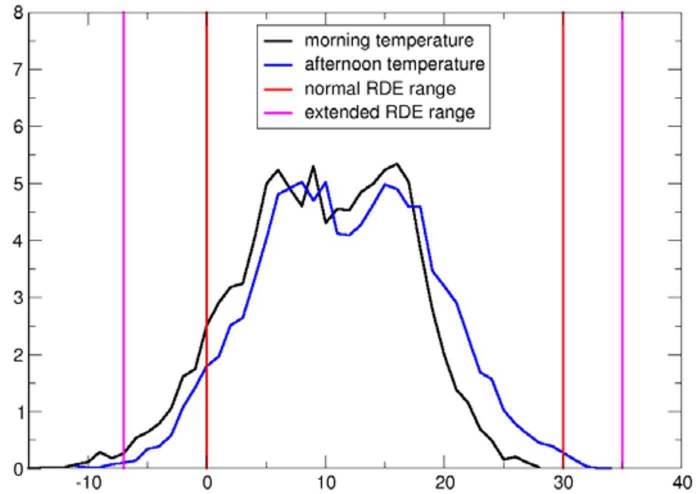

Figure 3: The distribution of temperatures in the Netherlands for the two main traffic periods in the morning (8:00) and the afternoon (17:00) based on KNMI data from De Bilt weather station. Below zero temperatures occurs in 8% and 5% of the days respectively.

There is a lower pressure limit of 82,5 kPa which is comparable to the 1600m upper limit for altitude which is a limit set for emission control monitoring.

Conclusion
Ambient temperatures and ambient pressures are well-covered for the Netherlands, as well as all altitudes.

3.3 Data exclusion: Power threshold

For the current 'step C' PEMS test the power threshold is 20%. The evaluation of the total trip must be done with at least 50% valid windows. If this is not reached, the power threshold must be lowered in steps of 1% to a minimum of 15% until 50% valid windows are obtained. If these 50% valid windows are not obtained, when the power threshold is minimized to 15%, the test is void.
For the new 'step D' PEMS test, the power threshold is fixed at 10% (2019). This means that MAW (Moving Averaging Windows) with an average power lower than 10% will be excluded from the pass-fail evaluation. The final pass-fail evaluation of the total trip must contain at least 50% valid windows. This means that half of the MAW data in theory may be excluded from the evaluation due to a low average power. This excluded data would represent much more than half of the data of a test trip (duration of one window plus the duration of 50% of the remainder of the time).

The new PEMS requirements (2016/1718, as of step C) however require at least one window with urban driving to be part of the pass-fail evaluation, which means that at least one MAW with urban driving cannot be excluded by one of the rules for data-exclusion.
The threshold of 10% is too high for some types of vehicles with typical low speed, low load operation. For instance, refuse collection vehicles (RCV) that operate in urban areas at very low average speeds and some heavy city bus lines may be operated under such conditions. An evaluation of real-world driving with RCVs' showed the fraction of driving in several average power bands.

Table 4: Average engine power of refuse collection vehicles during real world operation. On average the power demand is low. For one vehicle (B) about half of the time the power is below 10% while for another (C) the power is half of the time below 20%. The distribution of average engine power depends on the actual cycle and auxiliary power. Lowering the power threshold from 20 to 10% already brings an improvement but for some applications may not be sufficient.

% Engine power (30 minute windows)	Euro VI diesel N3 A	Euro VI LNG N3 B	Euro VI diesel N3 C	Euro VI diesel N3 D	Euro VI diesel N3 E	Euro VI diesel N3 F	Euro VI diesel N3 G	Euro VI diesel N3 H
<10	10%	9%	2%	54%	24%	100%	15%	15%
<15	61%	21%	25%	67%	56%	100%	44%	63%
<20	86%	49%	45%	83%	76%	100%	84%	89%
>=20	14%	51%	55%	17%	24%	0%	16%	11%

Table 5: Average engine power of M3 buses during real world operation. Lowering the power threshold from 20 to 10% already brings an improvement but for some applications may not be sufficient.

% Engine power (30 minute windows, A to D and MAW E and F)	Euro VI diesel M3 A 12m bus, city buslines	Euro VI diesel M3 B articulated bus 18m, city buslines	Euro VI diesel M3 C 12m bus, regional bus lines	Euro VI diesel M3 D 12m bus	Euro VI diesel M3 E Articulated bus 18m,	Euro VI diesel M3 F city and regional buslines (~50% payload)	Euro VI diesel M3 G city and regional buslines (~50% payload)
<10	2%	2%	2%	2%	2%	0%	45%
<15	15%	18%	25%	25%	14%	46%	99%
<20	49%	67%	76%	61%	58%	90%	100%
>=20	51%	33%	24%	39%	42%	10%	0%

The current data set does not contain a lot of real-use data of long-haulage trucks. It is recommended to collect with SEMS data of main stream long-haulage trucks in the Netherlands and to investigate the data for possible events where the average power drops below 10 or 20%.

Conclusion
For some special applications, the average engine power may be lower than the future threshold of 10%. Therefore, the PEMS test does not cover real-driving for those applications. For main stream long haulage trucks more data is needed from real operation to determine if and how much these vehicles operate at average engine power lower than the threshold.

3.4 Data exclusion: 90-% rule

10 % of the MAW with the highest emissions have to be excluded from the pass-fail evaluation. In a PEMS trip this represents a substantial share of driving, namely the duration of one window added with the duration of 10% of windows of the remainder of the trip. If one window lasts say half an hour and a total trip two and a half hours, in total 20%+10%=30% of the data is excluded.
For the new PEMS it is required that one MAW with only urban driving must be part of the evaluation after 10% data-exclusion.

Conclusion
The 90% rule excludes more than 10% of the test data.

3.5 Summary 'data exclusions'

Substantial amounts of data (MAW) that represent periods of normal operation may be excluded from the pass-fail evaluation:

- Cold start; the first 10 to 15 minutes after an engine cold start. For a handful of vehicles under different types of operation the cold start constitutes around 17% of total NO_x emissions under mild ambient conditions in the Netherlands. Inclusion of the cold start at mild ambient temperatures (20-30 °C) is scheduled.
- 10-percentile of the MAW due to the 90-percentile rule.
- From 0% to a maximum 50% of all MAW with an average power lower than 20-15% for the current PEMS test and lower than 10% for the new PEMS test.

3.6 Moving Averaging Window

Because emissions are averaged in a 'window' that last around half an hour, short excursions under typical load conditions are averaged out. Whereas average low emissions are important on a city level and for background concentrations of NO_2 short emissions excursions may contribute to local high ambient concentrations of NO_2 and NO, especially when due to local traffic conditions (traffic jam, traffic lights) consistent low load operation is forced. Due to 'averaging' temporal emissions excursions are therefore not controlled.

3.7 Trip

For the new PEMS test, a trip needs to consist of urban driving, followed by rural driving and motorway driving. Shares in terms of % of total trip time are defined for each segment and the margin for each segment is 5% point. Another trip order may be used upon agreement of the TAA, but a trip shall always start with urban. The N3 category has a small share of urban driving which means that the data of urban driving has a small part in the pass-fail evaluation. This is caused by the fact that a MAW may last longer than the urban part and therefore a MAW consist of a mix of urban and rural driving. Also urban data may be totally excluded from the pass-fail evaluation due to the 90% rule (10% of highest MAW are excluded from the pass fail evaluation). For the new PEMS test (step C) this is tackled by adding a requirement that there must be a MAW with only urban operation after applying the 90% rule.

Table 6: Table with required time shares and range for average speed per trip segment. Trip segment shares may deviate 5% point. To determine the segments, the period with an engine coolant temperature below 70 C is excluded. Between brackets the trip shares proposed for transposition in ECE Regulation 49.

	Urban	Rural	Motorway
Average speed range	15-30 km/h	60-90 km/h	>90 km/h
M1, N1	34 %	33%	33%
Average speed range	15-30 km/h	45-70 km/h	>70 km/h
Maximum		75 km/h	
N2, M2, M3	45%	25%	30%
N3	20%(30%)	25%	55%(45%)
M2, M3, class I, II and A	70%	30%	

The parts can be determined by two methods:

1. geographical coordinates (map) or
2. first acceleration method to a higher velocity.

In the case of the first method, urban may not contain more than 5% of the segment time speeds higher than 50 km/h and rural not higher than 75 km/h. For the second method 55 and 75 km/h are the speeds above which a transition occurs to respectively rural and motorway. For M1 and N1 these speeds are 70 and 90 km/h respectively.

A trip shall last between 4 and 7 times the time that is needed to procedure the work equivalent to one WHTC test. That means that a trip last longer when an engine drives on average at a higher power than for a WHTC test and vice versa.

The rural segment is limited to 75km/u, while in the Netherlands most rural roads have a speed limit of 80 km/h. Trucks and buses drive faster than 75 km/h on these roads. Some smaller rural roads have speed limits of 60 km/h, but these roads are typically only for local traffic and probably have a small share in total mileage of HDV driving in the Netherlands.

The range for the average speed of the urban trip is not sufficient for refuse collection vehicles (RCV) and some heavy bus lines. These types of operation are characterized by lower average speeds than the average speed range that is required. SEMS tests over real operation over longer periods of time showed average speeds of RCV from 7 to 17 km/u depending on the type of refuse collection. Also heavy city bus lines showed average speeds below 15 km/h (13 km/h in the case of a typical line that runs in a busy city centre).

Trips in the real-world are most likely different than the trips used for the PEMS test. In daily operation trips may have different shares of U/R/M operation and different orders of these types of operations. Different trip shares is defined for different legislative categories. A legislative category may constitute different types of vehicles. For instance, both long-haul vehicles (tractor semi-trailer, rigid-trailer) and refuse collection vehicles are N3 vehicles and would have to be tested over

an N3 trip (U/R/M = 20/25/55% +/-5% point). This distribution of trip shares is not representative for the operation of an average RCV.
For buses and RCV’s there are no requirements that the vehicle must be operated as they do in daily operation. Buses: bus stops, door openings, passengers embarking and disembarking. RCV: low speed driving, frequent stops, PTO operation, garbage intake.

Conclusion trip requirements
The trip requirements do not completely cover the Netherlands situation:
- The requirements for rural driving only represents part of typical rural driving in the Netherlands.
- The requirements for urban driving do not fully cover the real operation of RCVs and buses as average speeds lower than 15 km/h and above 30 km/h are outside of the scope.
- The test trips may not match the typical operation of a vehicle type.
- There are no requirements that demand the replication of normal operation in the test

3.8 Driving style

The requirements do not mention driving style. For the PEMS test a driver needs to be a skilled driver. Variations in driving style do not need to be tested.

3.9 Payload

In the new PEMS test at type approval test payloads shall be 50-60% of the difference between the technically permissible maximum laden mass and the mass in running order. For the in-service conformity test there a range of 10-100% prescribed. This range covers most operations.

3.10 Vehicle configurations

There are only few requirements with regard to vehicle configurations. Tractors have to be tested with a semi-trailer. This means that driving without is excluded from the PEMS test. For rigid trucks, which can pull a trailer, LZV, or other special configurations there are no specific requirements.

3.11 Alternative emission strategy AES or auxiliary emission control strategies.

With regard to AES (AECS in ECE R49 regulation) there are some allowances with regard to operating conditions under which emissions control systems do not need to be active. It should be examined if those conditions overlap the ones of the ISC PEMS test, and what takes precedence. Are there any conditions that are within the scope of the PEMS test conditions which could fall under AES or AECS?

EC/582/2011 (“…2.4. "*Auxiliary Emission Strategy*" (AES) means an emission strategy that becomes active and replaces or modifies a base emission strategy for a specific purpose and in response to a specific set of ambient and/or operating conditions and only remains operational as long as those conditions exist;
2.5. "*Base Emission Strategy*" (BES) means an emission strategy that is active throughout the speed and load operating range of the engine unless an AES is activated;…”)

3.12 Overview of on-road PEMS test requirements for TA test and ISC test and coverage of conditions in the Netherlands

Table 7: Overview of on-road PEMS test requirements for TA test and ISC test and coverage of conditions in the Netherlands.

	Test requirement	*Real-world*	*Coverage*
Data exclusion: Cold start	Cold start performed but not evaluated	Cold starts contribute significant to total NO_x emissions	No
Data exclusions: Ambient temperature, pressure and altitude	Temperature: -7 to 38 °C Pressure: >82.5 kPa Altitude: <1600m	-15 to 40 °C > 82.5 kPa (no high mountains, see next) -7 (Zuidplaspolder) to 322m (Vaals)	Yes. Most ambient circumstances are covered
Data exclusion: Power threshold	<20 to <15% <10% (2019) Minimum 50% valid windows	All emissions	Level of coverage largely depends on typical operation. But substantial data may be excluded (0-50% of MAW)
Data exclusion: 90-% rule	10-% of MAW with highest emissions are excluded.	All emissions.	Partial. 10% of the MAW which means more than 10% of the test data with the highest emissions is excluded.
Moving Averaging Window (MAW)	Emissions are averaged in windows. Duration depends on average power in a window.	Local emissions on street level as well as local and regional average emissions contribute to local and background ambient concentrations	Partial. Local, temporal emissions are averaged out in MAW.

Test trip: shares	Trip with a certain defined share of urban, rural and motorway driving depending on EU category N1, N2, N3, M2, M3	Shares are different for special vehicles: RCV City distribution City bus Coach	Partial
Test trip: sub trip order	Fixed order U, R, M	Depends on operation	No
Test trip: average speed boundaries	Urban: 15-30 max 50 Rural: 45-70 max 75 Motorway: >75	RCV and city buses 7-25 NL Rural max speed >75 Motorway sometimes lower than <75 due to congestion	Partial
Driving style	Skilled driver	Unknown. Assumed a mix of driving styles	Unknown
Payload	TA 50-60%, ISC 10-100%	0-100%	Yes, mostly. Only by the latest amendment EC/2016/1718
Vehicle configurations	Most representative configurations	All configurations	Less representative vehicles configurations possibly not tested. Examples: LZV, RCV, tipper, 8x4 etc.

4 Is real-world test beating possible?

A theoretical exercise needs to be done to answer this question, as for HDV there is almost no evidence of beating. From the past, there is one example of a truck that used dual engine control mapping for which legislation at that time did not accommodate [Riemersma, 2006][5]. The engine could be run in two distinctive settings and an auto mode. The settings could be selected by a switch on the dashboard. The engine complied in each of the distinctive settings, but in auto mode the NO_X emissions exceeded the limits. Partly on the basis of these findings a modification of Directive 1999/96/EC was adopted, which excluded dual control strategies for the future. In theory, an on-road test can be ‘beaten’ if a vehicle can detect that a (PEMS-) test is being performed and an emission control system may be adjusted to only operate well, for instance dose sufficient Adblue to reduce the engines NO_x emissions, under the conditions of a PEMS test. Also for the PEMS test at type approval an engine system or parts of thereof may be chosen such that emissions are lowest.

The next methods can, in theory, be used to detect a PEMS test:

- Geofencing. Modern trucks and buses may be equipped with geofencing. This technology is primarily used as to be of benefit for the environment. As an example, a partial zero emission vehicle, equipped with geofencing may be forced to drive in zero emission mode in urban areas. In theory, this technology may be used to determine whether a vehicle is driving in the vicinity of an Emission Testing Laboratory, a Technical Service or on a test circuit.
- OBD connection detection. ECU detects that CAN messages are requested, so it can be detected that a PEMS CAN interface unit is attached to the CAN/OBD connector.
- Detection of typical test conditions of the PEMS test. For instance test duration, speed boundaries, ambient condition boundaries.

[5] Iddo Riemersma, In Use Compliance programme for trucks 2001-2004, TNO report TNO 2018 R10550, April 18, 2006

5 Is a further tightening of the limits for NO_X feasible?

5.1 Major regulations world-wide

The major regulations regarding tail-pipe noxious emissions of HDV have been developed in the US, Japan and the EU, with the rest of the world more or less following one of these major regulations. In addition, in UN-ECE working groups world-wide emissions legislation focusses on world-wide harmonized of testing procedures, rather than on standards or actual limit settings. In a few parts of the world the implementation of more stringent requirements are discussed.

5.2 US CARB (California Air-Resources Board)

In 2013, the California Air Resources Board (CARB) adopted optional low oxides of nitrogen (NO_x) emission standards for heavy-duty engines. (0.02 g/bhp.hr, which equals 0.027 g/kWh. This is 6% of the Euro VI limit of 0.46 g/kWh.)
The goal of CARB is to encourage engine manufacturers to introduce new technologies to reduce NOx emissions below the current mandatory heavy-duty diesel engine emission standards for US2010 (model years 2010 and later). August 2017, a handful of engine families (3 x CNG, 1 x LPG) were certified to the optional low-NO_X standard.

US CARB is considering a further tightening of the mandatory NO_X limit for HDV with -90% and more focus in the testing procedures on low load, low speed operating conditions which are the most challenging conditions to keep SCR system working [CARB 2015]. A lowering of -90% from 0.27 g/kWh (US2010) comes down to a limit of 0.02 g/bhp.hr which is as low as the current optional low NO_X standard. CARB investigated the technical feasibility to achieve the lower limits under given severe driving conditions. CARB also investigated a cycle with lower load and possible alternatives for the NTE (Not-to-exceed). Adoption of new rules for the heavy-duty emission regulations is expected in 2019 and implementation in 2023 to 2027 [Johnson, 2016]. California presses EPA to adopt the more stringent standard because many trucks enter California from other states.

Regulatory Development Plan

Hearing	Action	Implementation
Actions Taken	Optional Low NO_X Standards: (50%, 75% & 90% lower)	Currently Certifying Engines
	Innovative Technology Regulation	Undergoing final administrative steps
2017	Updates to Smoke Opacity Programs	2018
	Warranty Updates	2018 and onwards
	CA Heavy Duty Phase 2 GHG alignment	Paralleling federal program
2019	Low NOx Engine Performance Requirements	2023 and onwards
	Low Load Certification Requirements	
	In-Use Compliance Program (currently NTE)	
	Warranty/Durability/ Useful Life Period Definitions	
2020	HD Inspection/Maintenance Program	Post 2020

Figure 4: CARB regulatory plan (source Yoon, Robertsson, 27th CRC REAL WORLD EMISSIONS WORKSHOP Long Beach, CA, March 26 - 29, 2017March 2017).

The plans to further tighten the requirements for NOx origin from a broader investigation into the ways to reduce overall NO_X emissions in California in order to fight the air quality problems that exist due to the geographical location, the high economic activity and transport activity and the mix of petrol and diesel emissions that tends to increase ozone formation.

In a diesel technology screening SwRI identified multiple pathways to achieve the 90% reduction for NOx emission (below 0.02 g/bhp.hr):

- Thermal management
  - supplemental heat (electric and fuel fired burners, post injection),
  - exhaust heat retention, (insulation of exhaust manifold and piping),
  - intake throttling,
  - variable turbo,
  - turbo charger by-pass.
- Advanced aftertreatment systems
  - PNA (Passive NO_x adsorber),
  - Advanced SCR,
  - Close coupled SCR
  - SCRF
  - Alternative (gaseous) ammonia sources
  - Urea delivery
  - EGR

Southwest Research Institute is running (July 2017) a demonstration programme with its ‘Final ARB Low NOx configuration’, but ran into an incident with the emission control system during the aging test. Further investigation of catalyst aging over the full useful-life is said to be needed.

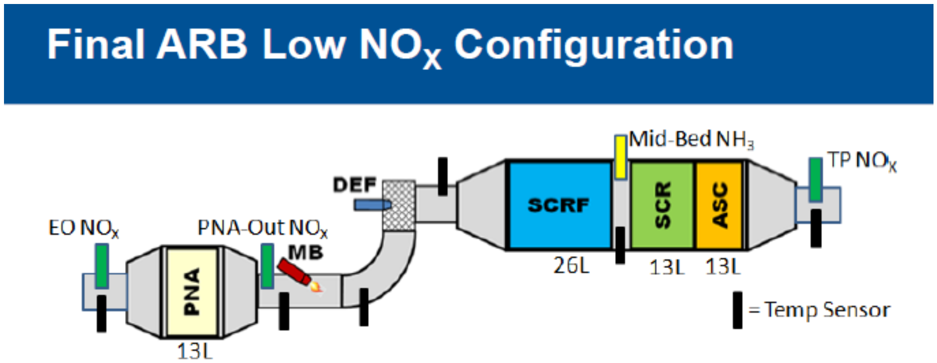

Figure 5: Final ARB Low NOx Configuration which consist of a passive NOx adsorber (PNA), a mini-burner (MB), DEF dosing combined SCR catalyst + particle filter (SCRF) an SCR catalyst and an ammonia slip catalyst (ASC). Source: Achieving ultra-low NOx emission levels with a 2017 on-highway TC diesel engine, SAE 2017 presentation, C.A. Sharp.

5.3 China VI

For China IV and V PEMS tests are described in DB11/965-2013. China VI is comparable to EU Euro VI emissions standards (WHTC NO_x 0.46 g/kWh).
For China VI, however, the Ministry of Environmental Protection plans to go beyond Euro VI by additional enforcement and compliance by means of remote OBD[6].

5.4 Other nations

Other nations more or less follow or lag behind the US and EU legislations.
For Japan the Post post new long term (PPNLT) step has a NOx limit of 0.4 g/kWh over the WHTC test. Japan considers PEMS real road tests in the first half of 2017[7]. India follows EU regulation, and plans Euro VI and a PEMS in-use test for 2020.

Conclusion
From the developments in the US, California it seems that substantial reduction of the NOx limits combined with more severe testing are achievable with advanced NOX abatement technologies. The current low NOx configuration uses a combination of a passive NOx adsorber (PNA), a mini-burner (MB), advanced AdBlue dosing in a combined SCR catalyst + particle filter (SCRF) an SCR catalyst and an ammonia slip catalyst (ASC). The durability of this system still has not been proven though.

[6] http://www.meca.org/regulation/mobile-source-regulatory-comparison.
[7] JAMA –JARI presentations 26 jan 2017: Introduction of the PEMS study for HDV in JAMA/JARI

The US CARB 'low NO_X configuration' aims at overall lower NO_X emissions at warm operation but also at a lower NO_X emissions under low load operation and after a cold start, especially for vocational vehicles. This means that if these technologies have been proven to work cost-efficiently and be durable over the life time of a vehicle, these technology could be considered for dealing with conditions that are now not covered by the EU real-world test with PEMS and result in lower NOx emissions under these conditions as well as yield on average lower NO_X emissions by all heavy-duty vehicles as well.

6 Conclusions

Coverage of the Dutch conditions by the real-world PEMS test
The conditions that are still not controlled by the new amendment (2016/1718) 'Step C' in the real-world test and are considered normal operation in the Netherlands, are:

- The cold start. Until now there are no provisions for taking into account the cold start and warm up period. Driving with an engine coolant temperature below 70 °C is not in the scope of the evaluation of the real-world test.
- Up to 2019, windows with an average power lower than the 'power threshold' of 20 to 15%. As of 2019, windows with an average engine power lower than the 'power threshold' of 10%, which still occurs for significant shares of real-world operation for special applications such as refuse collection vehicles. A power threshold of 10% excludes conditions where the average engine power in a 'window' is lower than 10%. This power threshold comes with the additional requirement to have 'at least 50% valid windows' which means that another 50% of windows (more than 50% of the test time) may be excluded from the pass-fail evaluation of the real-world emissions test.
- 10 percentile of the windows where the emissions are the highest on average (in a moving Averaging Window), because these 'windows' are excluded from the pass-fail evaluation. Obviously, those emissions can be emitted under normal conditions.
- In practice, the successive application of the above mentioned rules of evaluation result in the exclusion of the majority of the data with the poorest emission performance.
- Driving in urban driving conditions with an average speed lower than 15 or higher than 30 km/h. Especially, lower driving speeds are of concern. Buses on busy city lines and refuse collection vehicles working city garbage collection routes have average speeds lower than 15 km/h.
- Temporal and local emissions are not controlled. The PEMS pass-fail procedure average emissions in Moving Averaging Windows of around half an hour. Temporarily, on the time scale of 'driving through a street', emissions may be high.
- PN emissions are not yet controlled in the real-world PEMS test.
- Important conditions which are covered:
- One moving averaging window with urban driving is mandatory part of the pass-fail evaluation, since the immediate entry into force of 2016/1718.
- Typical Dutch ambient conditions and altitudes are mostly within the real-world test boundaries.
- Payload. Since 2016/1718, the 'normal conditions of use' include payloads of 10 to 100%, which means vehicles needs to compliant regarding in-service conformity in this payload range. For the type approval test the payload needs to be in the range of 50-60%.
- For step 'D', which accounts for type approvals for all new vehicle as of 1 September 2019, the power threshold is lowered from 20% (up to 15%) to 10%. This means that moving windows with a lower average power need to be taken into account for the pass-fail evaluation.
- Further improvements, i.e. the inclusion of cold start and implementation of PN measurement is scheduled for 'Step E', expected due date September 2020.

Is further reduction of NO_x emissions levels of HDV achievable?
The 'low NO_X configuration' for heavy-duty vehicles of US CARB is aimed at overall lower NO_X emissions at warm operation but also at a lower NO_X emissions under low load operation and after a cold start. The most ambitious target is to obtain -90% reduction against the current US2010 limit (6% of the Euro VI limit of 0.46 g/kWh). This means that if these technologies have been proven to work cost-efficiently and be durable over the life time of a vehicle, these technology could be considered for dealing with conditions that are now not covered by the EU real-world test with PEMS and yield on average substantially lower NO_X emissions.

Is beating a real-world test possible?
In theory it is possible. Technically, there are several ways for a modern truck to detect a road test with PEMS. So far, no evidence for beating a PEMS test was reported.

7 References

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[CARB] https://www.arb.ca.gov/msprog/hdlownox/hdlownox.htm https://www.arb.ca.gov/research/veh-emissions/low-nox/low-nox.htm

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8 Signature

The Hague, 15 November 2018

TNO

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A Overview of requirements in the EU HD emissions legislation

- Type approval laboratory engine test: World harmonized driving cycles WHSC, WHTC (R49 Annex 4B),
- Type approval PEMS test,
- In-service conformity: PEMS testing after 18 months of first registration over useful life,
- Requirements to ensure the correct operation of NOx control measures,
- Requirements regarding emission strategies: AES (Auxiliary Emission Stategy), BES (Base Emission Strategy). AECS and BECS in R49,
- Requirements to limit off-cycle and in-use emissions, WNTE Control area and limits,
- Off-cycle laboratory testing of engines and vehicles at type approval,
- On-board diagnostics including OTL's,
- Additional monitoring requirements (EGR flow, EGR cooler performance, injectors, boost pressure, DPF dp),
- Conformity of production,
- Durability of pollution control devices,
- Access to OBD and access to vehicle RMI,
- Crankcase emissions,
- Measurement of net engine power,
- Replacement pollution control devices.

For heavy-duty engines and vehicles the emission regulation applies to:

- Heavy-duty vehicles and engine systems as a separate technical unit,
- Motor vehicles of category N1, N2, M1 exceeding a reference mass of 2610 kg and of category N3 , M2 and M3,
- Fuels covered: Compression Ignition and Spark Ignition engines running on: Natural gas (CNG, LNG), diesel reference fuel B7, Ethanol E85, ED 95, Petrol E10, LPG, dual-fuel. For market fuels that do not comply with EN590, EN228 and Directive 98/70/EC additional declarations and demonstrations are requested from the manufacturer,
- Extension of EC type approval is possible to ECE R83 to vehicles with a reference mass lower than 2840 kg, but higher than 2610 kg,
- Determination of FC and CO_2 and provisions on extension of EC type approval for vehicle with reference mass of 2380 to 2610 kg.