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TNO report

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On road emissions of 38 petrol vehicles with high mileages

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Samenvatting

Grotere steekproef na eerder uitgevoerd onderzoek
Dit onderzoek is een vervolg op het door TNO in 2018 gerapporteerde onderzoek waarin twaalf oudere benzinevoertuigen op een rollenbank zijn getest op hun NO_x emissie. Twee van de twaalf geteste voertuigen werden toen aangemerkt als ‘high- emitter’ (zij lieten een zeer hoog NO_x emissieniveau zien) en enkele andere voertuigen vertoonden ‘enigszins verhoogde’ NO_x emissies. Op basis van deze steekproef was echter onduidelijk in hoeverre verhoogde NO_x emissies voor zouden komen in de gehele Nederlandse vloot van oudere benzinevoertuigen met driewegkatalysator. In opdracht van het Ministerie van Infrastructuur en Waterstaat heeft TNO nu ter aanvulling uitlaatemissies gemeten van 38 oudere benzinevoertuigen.

Primaire onderzoeksvraag was of benzinevoertuigen bij een toenemende leeftijd en kilometerstand nog dezelfde emissieniveaus laten zien als bij hun typegoedkeuring, of dat deze door verouderingseffecten oplopen. Om deze vraag te kunnen beantwoorden zijn emissiemetingen uitgevoerd op de openbare weg waarbij ieder van de te testen voertuigen was uitgerust met een mobiel emissiemeetsysteem. De metingen zijn verricht aan voertuigen met een driewegkatalysator en bouwjaren van 1998 tot 2017. Het betrof acht Euro 2, negen Euro 3, zestien Euro 4, vier Euro 5 personenauto’s en één Euro 6 personenauto. De voertuigen hadden een gemiddelde kilometerstand van ruim 220.000 km en een gemiddelde leeftijd van ca. 16 jaar.

Naast beantwoording van de primaire onderzoeksvraag is gevraagd ook suggesties te gegeven voor meettechnieken die kansrijk zijn voor een periodieke test op NO_x -emissies bij benzinevoertuigen.

Om een typegoedkeuring te verkrijgen moesten deze voertuigen voldoen aan gestelde emissielimieten tijdens een ‘NEDC rollenbanktest’ in het laboratorium. Echter, bij een kilometerstand hoger dan 100.000 km hoeven deze voertuigen niet meer te voldoen aan een duurzaamheidseis die gecontroleerd wordt in ‘In-Service Conformity’. Voor uitlaatgasnabehandelingssystemen geldt verder een effectieve duurzaamheideis voor een kilometerstand tot aan 160.000 km.

Resultaten en conclusies
In dit vervolgonderzoek, met 38 voertuigen, is een lager aandeel auto’s met een sterk verhoogde NO_x-uitstoot gevonden dan bij het eerste onderzoek met twaalf auto’s. Anderzijds was het aandeel voertuigen met verhoogde emissies (met emissies tot een factor 2 tot 4 boven de oorspronkelijke waarde), wel groter dan eerder gedacht. Aangezien het rollenbank testprogramma dat door TNO in 2018 is uitgevoerd soortgelijk onderzoek betrof, zijn resultaten van beide programma’s samengevoegd. De resultaten van de in totaal 50 geteste voertuigen leiden tot de volgende conclusies:

Gemiddelde NO_x emissies van oudere benzinevoertuigen zijn hoog:
Van de in totaal vijftig geteste voertuigen is de gemiddelde NO_x emissie 200 mg/km. De limietwaarden verschillen per euroklasse en liggen tussen de 60 en 150 mg/km.

De gewogen limietwaarde over de euroklassen van de geteste voertuigen is 115 mg/km. De gemiddelde conformiteitsfactor (CF) is daarmee 1,74. Dit betekent dat de gemeten gemiddelde NO_x emissie 74% hoger is dan de gewogen limietwaarden van de typegoedkeuringstest op de rollenbank. Ter vergelijking: emissies van 200 mg/km zijn hoger dan die van een gemiddelde moderne dieselauto (Euro 6D Temp).

Oudere benzinevoertuigen stoten gemiddeld meer NO_x uit dan vergelijkbare jongere benzinevoertuigen:
De gemiddelde NO_x emissie van de geteste oudere benzinevoertuigen van 200 mg/km is gemiddeld ca. twee keer hoger dan die van benzinevoertuigen die eerder zijn getest toen deze nog nieuw waren en nog maar lage kilometerstanden hadden. Deze voertuigen (die door TNO tot 2008 jaarlijks werden getest, en na die tijd met tussenpozen) lieten toen maar beperkte afwijkingen zien tussen de resultaten van typekeuringstesten en die van praktijkemissies.

Defecte voertuigen hebben grote impact op de gemiddelde NO_x emissie:
Veertig voertuigen hadden een normale (CF < 1) of iets verhoogde NO_x emissie (CF < 2) en zeven voertuigen een verhoogde NO_x emissie (CF = 2 – 4).
Drie voertuigen hadden een sterk verhoogde NO_x emissie. Twee van deze drie voertuigen waren afkomstig van het onderzoek uit 2018 en slechts één voertuig uit het nu afgeronde grotere vervolgonderzoek. Gezamenlijk hadden deze drie voertuigen een gemiddelde NO_x emissie van 1197 mg/km. De bijdrage van deze drie voertuigen (6% van het aantal geteste voertuigen) op de totale NO_x emissie van de vijftig geteste voertuigen is 36%.

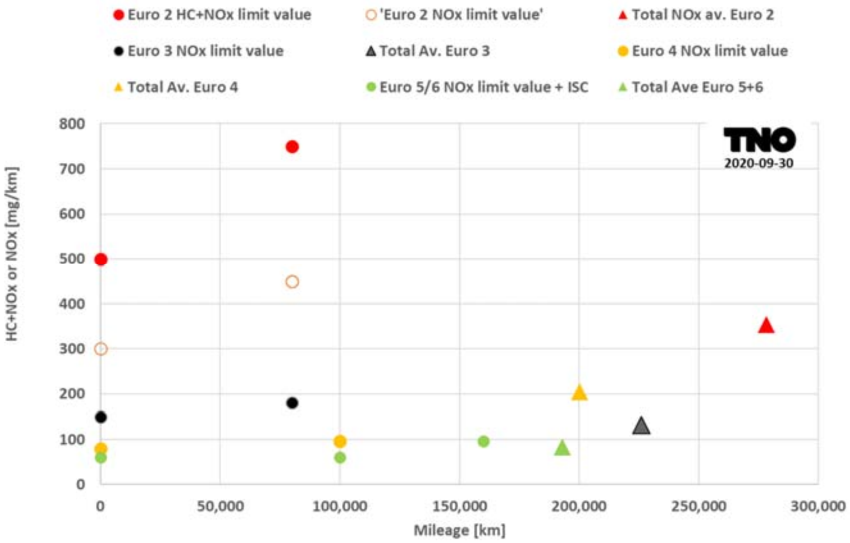
Geen aanwijsbaar verband tussen hoge NO_x emissies en voertuigparameters:
Uit de meetdata van de individuele voertuigen blijkt dat de gemeten NO_x emissies van de geteste voertuigen niet afhankelijk zijn van kilometrage (vanaf 160.000 km), voertuigleeftijd, Euroklasse, voertuigmerk of voertuigmodel. Omdat bij een groot aandeel van de geteste voertuigen ook de onderhoudshistorie niet of slechts deels aanwezig was, kon ook geen verband worden gelegd tussen onderhoudshistorie en verhoogde emissies.

Huidige duurzaamheidseisen voor emissies dekken de gemiddelde levensduur van een voertuig niet af:
In Figuur 1-1 zijn (met driehoekjes) de gemiddelde gemeten NO_x emissies per Euroklasse weergegeven in relatie tot de gemiddelde kilometerstand van de geteste voertuigen uit die klasse. Tevens zijn (met rondjes) de NO_x limietwaarden weergegeven, de oorspronkelijke waarden bij 0 gereden km's en de waarden met toegestane verouderingseffecten bij 80.000, 100.000 of 160.000 gereden km's (deze laatste afhankelijk van de betreffende Euroklasse).
De gemiddelde kilometerstanden van de geteste voertuigen uit de verschillende Euroklassen was 1,2 tot 3,5 keer hoger dan de kilometerstanden gespecificeerd voor de geldende duurzaamheidseisen. In de Nederlandse vloot van benzinevoertuigen vormen de geteste voertuigen qua kilometerstand geen uitzondering.

Vanuit de typekeuring is er dus geen referentiekader voor de beoordeling van de emissieprestaties van voertuigen met kilometerstanden hoger dan die van de duurzaamheidseisen.

Voor personen- en bestelwagens gelden deze slechts tot kilometerstanden van 80.000 tot 160.000 km (afhankelijk van de Euroklasse van het voertuig). Er zijn wel eisen vanuit het kader van periodieke controle maar die zien niet specifiek toe op sterk verhoogde NO_x-emissies. Verderop in de samenvatting wordt verdere aandacht besteed aan de eisen vanuit de periodieke controle (APK).

Een sportieve rijstijl resulteert in substantieel hogere emissies:
Vier voertuigen zijn getest met een normale en sportieve rijstijl. Een sportieve rijstijl resulteerde voor deze vier voertuigen in een toename van de emissies. Deze toename bedroeg gemiddeld voor $CO_{2:}$ +13%, voor $NO_{x:}$ +96% en voor NH_3 +39%. Hieruit blijkt dat een sportieve rijstijl tot (substantiële) toenames van de gemeten CO_2, NO_x en NH_3 emissies leidt ten opzichte van die bij een normale rijstijl.



Figuur 1-1: NO_x limietwaarden per Euroklasse (rondjes), zonder en met toegestane veroudering in relatie tot de kilometerstand. Ook is aangegeven, per Euroklasse, de gemiddelde gemeten NO_x emissie (driehoekjes) in relatie tot de gemiddelde kilometerstand van de geteste voertuigen uit die klasse. De NO_x limietwaarde van Euro 2 voertuigen is geschat omdat wettelijk de HC+NO_x limietwaarde is vastgelegd.

Repareren loont:
Reparatie van voertuigen met zeer hoge NO_x emissies bleek een sterk positief effect te hebben. Bij drie van de vier gerepareerde voertuigen resulteerde reparatie in een gemiddelde daling van de NO_x emissie met 37, 92 en 93%. Bij één voertuig lag de nadruk op reparatie van het EGR (Exhaust Gas Recirculation) systeem en bij twee voertuigen is de driewegkatalysator vervangen. De gemiddelde NO_x emissie van de vijftig geteste voertuigen daalde na de reparaties van 200 naar ongeveer 130 mg/km. De bijbehorende gemiddelde conformiteitsfactor (CF) is dan 1,15.
De tijdens het onderzoek uitgevoerde reparatie van een vierde voertuig bleek niet effectief. Vermoedelijk had, naast de uitgevoerde reparaties aan lambda sensoren, ook de driewegkatalysator een verminderd omzettingsrendement. Deze kon binnen het project helaas niet meer worden vervangen.

Uitlezen OBD systemen niet bruikbaar als indicatie voor verhoogde NO_x emissies:
Er zijn Europese eisen ten aanzien van de periodiek controle (APK) van de voertuigemissies. Voor benzineauto's vanaf 1993 moet hiervoor de zogeheten viergastest worden uitgevoerd. Voor auto's vanaf 2006 wordt in plaats van de viergastest bij de APK het EOBD-systeem (European On-Board Diagnostics systeem, kortweg OBD) uitgelezen. Indien uitlezen van de EOBD niet goed kan worden doorlopen of als emissie-gerelateerde foutcodes worden gevonden, dan wordt alsnog de viergastest uitgevoerd.

Uit het onderzoek blijkt dat On Board Diagnose (OBD) systemen niet in staat zijn om aan te geven dat een voertuig verhoogde NO_x emissies vertoont. Twee van de drie geteste voertuigen met zeer hoge NO_x emissies hadden geen actieve OBD codes. Ook bij de meeste geteste voertuigen met sterk verhoogde NO_x emissie gaf het betreffende OBD systeem geen meldingen.

Huidige APK viergastest niet geschikt voor detectie van verhoogde NO_x emissies:
De huidige viergastest kan voertuigen met verhoogde NO_x emissies nauwelijks detecteren. Slechts één van de 50 geteste voertuigen, namelijk het voertuig met een NO_x emissie op de weg van 1267 mg/km, werd in de APK emissietest afgekeurd. Dit voertuig was vier maanden eerder met een geforceerde preconditionering (het voertuig was voor de test extreem opgewarmd) in de reguliere APK test goedgekeurd. Ook de in 2018 geteste voertuigen met zeer hoge NO_x emissies waren in de APK goedgekeurd.

In de huidige APK viergastest wordt door middel van een CO-meting het oxiderend vermogen van een katalysator gecontroleerd. Gemeten CO concentraties in een viergastest bleken niet te correleren met gemeten NO_x concentraties. Anders gezegd: de CO-meting is niet bruikbaar om verhoogde NO_x emissies te detecteren.

De huidige lambda APK limietwaarden zijn niet passend:
Het momenteel in de APK emissietest toegestane venster voor de lambda-waarde bij verhoogd stationair toerental loopt van 0.965 tot 1.039. Het is de verwachting dat aanscherping van deze APK lambda limietwaarden, in de vorm van een verkleining van dit interval, kan bijdragen aan detectie van een groter aandeel voertuigen met hoge NO_x emissies.

Verbetering van de APK emissietestprocedure is naar verwachting effectief voor betere detectie van benzinevoertuigen met een NO_x emissieprobleem:
De huidige testprocedure van de APK viergastest leidt in de praktijk tot niet éénduidige testresultaten.

Onder andere de volgende aspecten zijn denkbaar ter verbetering van de procedure:
- Het hanteren van een minimale stabilisatie- en meettijd.
- Het voorschrijven van de meetfrequentie.
- Het definiëren van de volgorde en de tijdsduur van de testen bij hoog en laag stationair toerental.
- Het stellen van eisen aan de preconditionering van de katalysator (in de huidige testprocedure worden minimumeisen gesteld waardoor niet realistische (excessieve) preconditionering is toegestaan.

Stationaire testen met koude start zijn mogelijk toepasbaar als screeningstest:
Bij stationaire testen die aanvangen met een koude motor waarbij ongeveer 20 minuten lang, bij stationair toerental, opwarming van de drieweg katalysator plaatsvindt, was de afname van de CO, THC en NO_x concentraties bij de meeste geteste voertuigen hoger dan 80%. Voor enkele voertuigen waren deze afnames 50 tot 80%. Slechts één voertuig had zeer lage afnames van minder dan 20%.
Deze opwarmtest is mogelijk een optie voor screening van voertuigemissies.

NH_3 emissies zijn relatief hoog in stadsverkeer en variëren sterk per type voertuig:
In het kader van stikstofdepositie is het interessant om te weten welke NH_3 emissies vanuit diverse bronnen optreden. Om die reden zijn in dit project eveneens NH_3 emissies gemeten. De gemiddelde NH_3 emissie van de 38 op de weg geteste voertuigen is 32.1 mg/km en per voertuig varieert deze van 1 tot 99 mg/km. In stadsverkeer was de gemeten gemiddelde NH_3 emissie 49 mg/km, op de buitenweg 22 mg/km en op de snelweg 21 mg/km.

Emissiefactoren beschrijven per component (bijvoorbeeld NO_x, NH_3) een gemiddelde uitstoot per type voertuig en type weg en worden gebruikt voor berekeningen ten behoeve van stikstofdepositie en luchtkwaliteit. De nu gemeten gemiddelde NH_3 emissies wijken af van de actuele waarden van NH_3 emissiefactoren, deze zijn momenteel voor verkeer in stad/buitenweg/snelweg 18.8, 19.6 en 35.8 mg/km. De nu gemeten waarden worden meegenomen als input voor de jaarlijkse bijstellingen van de emissiefactoren voor wegverkeer.
Verder blijken de NH_3 emissie van vier geteste voertuigen na een koude start relatief hoog te zijn. In de eerste 7.2 kilometer zijn deze gemiddeld ruim vier keer hoger dan bij eenzelfde test met warme start.

Aanbevelingen:

- Aangezien voertuigen met ernstige defecte emissiecontrolesystemen een grote invloed lijken te hebben op de totale emissie van benzinevoertuigen is het wenselijk meer informatie te verkrijgen over het aandeel van deze voertuigen in het Nederlandse wagenpark. Mogelijk bieden andere bronnen (zoals sluitende APK-databases) verder inzicht in het minimum aandeel voertuigen dat een defect emissiecontrolesysteem heeft.

- Om een betere detectie mogelijk te maken, in de APK, van voertuigen met een hoge NO_x emissie, wordt terugkeer naar uitvoering van de viergastest (in plaats van uitlezen van OBD) aanbevolen. Dit echter wel in combinatie met een verbeterde testprocedure. Het advies is om nader te onderzoeken hoe de huidige APK testprocedure voor de viergastest precies kan worden verbeterd. Meerdere aspecten om daarbij te betrekken zijn in dit rapport benoemd. Is detectie van voertuigen met een te hoge NO_x emissie beter mogelijk geworden, dan kunnen deze voertuigen daarna worden gerepareerd of, bij een niet oplosbare bron van hoge emissie, mogelijk uit het wagenpark verdwijnen.

Afsluitende informatie

Inzicht in emissiefactoren bij hogere kilometerstanden
Gemeten voertuigemissieniveaus worden gebruikt voor het opstellen van emissiefactoren. Emissies van benzinevoertuigen zijn in het verleden gemeten, deze voertuigen waren destijds slechts een paar jaar oud en hadden nog een lage kilometerstand.

Op basis van deze gegevens zijn toen emissiefactoren opgesteld voor de verschillende praktijksituaties op de weg. Het nu verkregen inzicht in de emissies van de geteste voertuigen bij hogere kilometerstanden is waardevolle informatie voor een bijstelling van de emissiefactoren ten gevolge van verouderingseffecten.

Waarmee zijn de emissies gemeten?
De voertuigen hebben een praktijkritcyclus op de openbare weg ondergaan.
Ook zijn APK emissietesten uitgevoerd. Bij de praktijktest op de openbare weg is gebruik gemaakt van een aangepaste versie van het ‘Smart Emissions Measurement System (SEMS) van TNO waarmee goede indicaties van NO_x, NH_3 en CO_2-emissies worden verkregen. Uit validatiemetingen met testapparatuur van een rollenbank is gebleken dat met het aangepaste meetsysteem beperkte afwijkingen in gemeten CO_2 emissies optraden van +6% tot +8% en voor NO_x emissies afwijkingen van -10% tot -14%.

Summary

Larger sample after previous survey
This study is a follow-up to the study reported by TNO in 2018 in which twelve older petrol vehicles were tested for their NO_x emissions on a roller dynamometer. Two of the twelve vehicles tested were then classified as 'high emitters' (they showed a very high level of NO_x emissions) and some other vehicles showed 'slightly increased' NO_x emissions. However, on the basis of this sample it was unclear to what extent increased NO_x emissions would occur in the entire Dutch fleet of older gasoline vehicles equipped with three-way catalytic converters. Commissioned by the Ministry of Infrastructure and Public Works, TNO has now additionally measured exhaust emissions from 38 older petrol vehicles.

The primary research question was whether petrol vehicles with increasing age and mileage, still show the same emission levels as at their type approval, or whether these increase due to ageing effects. In order to answer this question, emission measurements were carried out on public roads where each of the vehicles to be tested was equipped with a mobile emission measurement system. The measurements were carried out on vehicles equipped with three-way catalytic converters and years of construction from 1998 to 2017. Tested were eight Euros 2, nine Euros 3, sixteen Euros 4, four Euro 5 passenger cars and one Euro 6 passenger car. The vehicles had an average mileage of over 220,000 km and an average age of around 16 years. In addition to answering the primary research question, suggestions were also made for measurement techniques that may be suitable for periodic testing for NO_x emissions from petrol vehicles.

In order to be type-approved, these vehicles had to comply with set emission limits during an 'NEDC chassis dynamometer test' in the laboratory. However, at a mileage of more than 100,000 km, these vehicles no longer have to meet a durability requirement that is checked in 'In-Service Conformity'. Exhaust aftertreatment systems are also subject to an effective durability requirement for mileage up to 160,000 km.

Results and conclusions
In this follow-up study with 38 vehicles, a lower proportion of cars with greatly increased NO_x emissions was found than in the first study with 12 cars. On the other hand, the proportion of vehicles with increased emissions (with emissions up to a factor of 2 to 4 above the original value) was higher than previously thought. As the chassis dynamometer test programme carried out by TNO in 2018 involved similar research, results from both programmes have been combined. The results of a total of 50 vehicles tested lead to the following conclusions:

Average NO_x emissions from older petrol vehicles are high:
Out of a total of fifty vehicles tested, the average NO_x emissions are 200 mg/km. Limit values vary between Euro classes and are between 60 and 150 mg/km. The weighted limit value over the euro classes of the vehicles tested is 115 mg/km. The average compliance factor (CF) is therefore 1.74. This means that the measured average NO_x emission is 74% higher than the weighted limit values of the type approval test on the chassis dynamometer. In comparison, emissions of 200 mg/km are higher than those of an average modern diesel car (Euro 6D Temp).

Older petrol vehicles emit on average more NO_x than comparable younger petrol vehicles:
The average NO_x emission of 200 mg/km is on average about twice as high as that of petrol vehicles that were tested earlier when they were new and only had low mileages. Petrol vehicles tested annually by TNO until 2008, and intermittently after that time, showed only limited deviations between the results of type approval tests and those of real world emissions.

Defective vehicles have a major impact on average NO_x emissions:
Forty vehicles had normal (CF < 1) or slightly increased NO_x emissions (CF < 2) and seven vehicles had increased NO_x emissions (CF = 2 - 4).
Three vehicles had greatly increased NO_x emissions. Two of these three vehicles were from the 2018 study and only one vehicle from the now completed larger follow-up study. Together, these three vehicles had an average NO_x emission of 1197 mg/km. The contribution of these three vehicles (6% of the number of vehicles tested) to the total NO_x emissions of the 50 vehicles tested is 36%.

No demonstrable correlation between high NO_x emissions and vehicle parameters:
The measurement data of the individual vehicles show that the measured NO_x emissions of the tested vehicles do not depend on mileage (from 160,000 km), vehicle age, Euro class, vehicle make or vehicle model. Since maintenance history was not present or only partially present for a large proportion of the vehicles tested, it was also not possible to establish a link between maintenance history and increased emissions.

Current durability requirements for emissions do not cover the average service life from a vehicle:
Figure 1.1 shows (with triangles) the average measured NO_x emissions per Euro-class in relation to the average odometer value of the tested vehicles of that class. It also shows (with small circles) the NO_x limit values, the initial values at 0 km driven and the values with permissible aging effects at 80,000, 100,000 or 60,000 km driven (the latter depending on the Euro class concerned).

The average mileages of the tested vehicles of the different Euro-classes were 1.2 to 3.5 times higher than the mileages specified for the durability requirements in force. In the Dutch fleet of petrol vehicles, the tested vehicles are no exception in terms of mileage.

From the type approval point of view, therefore, there is no reference framework for the assessment of the emission performance of vehicles with odometer readings higher than those specified for the durability requirements. For passenger cars and vans, these only apply up to 80 000 to 160 000 km (depending on the Euro class of the vehicle). There are periodic inspection requirements but they do not specifically address significantly increased NO_x emissions. Further on in the summary, further attention is paid to the requirements from the periodic inspection (PTI).

A sporty driving style results in substantially higher emissions:
Four vehicles have been tested with a normal and sporty driving style. A sporty driving style resulted in an increase in emissions for these four vehicles. The average increase for CO_2 was +13%, for NO_x +96% and for NH3 +39%.

This shows that a sporty driving style leads to (substantial) increases of the measured CO_2, NO_x and NH_3 emissions compared to a normal driving style.

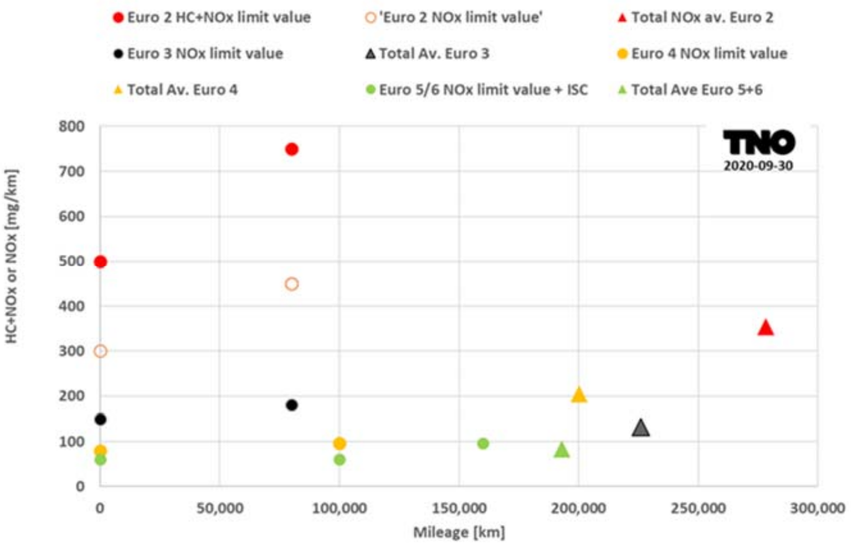


Figure 1-1: NO_x limit values (small circles) per Euro-class without and with permitted aging in relation to mileage. The average measured NO_x emissions per Euro-class (triangles) in relation to the average odometer value of the vehicles tested in that class are also indicated. The NOx limit value of Euro 2 vehicles is estimated because the HC+NO_x limit value is laid down by law.

Repair pays off:

Repairing vehicles with very high NO_x emissions proved to have a strong positive effect. Three out of four vehicles repaired resulted in an average reduction in NO_x emissions of 37, 92 and 93%. In one vehicle the emphasis was on repairing the EGR (Exhaust Gas Recirculation) system and in two vehicles the three-way catalytic converter was replaced. The average NO_x emission of the 50 vehicles tested decreased from 200 to about 130 mg/km after the repairs. The corresponding average compliance factor (CF) is then 1.15.

The repair carried out during the study on a fourth vehicle proved to be ineffective. In addition to the repairs carried out on lambda sensors, the three-way catalytic converter probably also had a reduced conversion efficiency. Unfortunately, it could not be replaced within the project.

Read-out of OBD systems could not be used as an indication for increased NO_x emissions:

There are European requirements with regard to the periodic inspection (PTI) of vehicle emissions. For petrol cars from 1993 onwards, the so-called four-gas test has to be carried out. For cars from 2006 onwards, instead of the four-gas test at the PTI, the European On-Board Diagnostics system (EOBD or OBD) will be read out. If it is not possible to read out the OBD properly or if emission-related error codes are found, the four-gas test will still be carried out.

The investigation shows that On Board Diagnostics (OBD) systems are not able to indicate that a vehicle exhibits elevated NO_x emissions. Two of the three vehicles tested with very high NO_x emissions had no active OBD codes.

Also for most of the vehicles tested with very high NO_x emissions, the OBD system in question did not give any reports.

Current PTI four-gas test is not suitable for detection of elevated NO_x emissions:
The current four gas test can hardly detect vehicles with elevated NO_x emissions. Only one of the 50 vehicles tested, namely the vehicle with a NO_x emission on the road of 1267 mg/km, was rejected in the PTI emission test. This vehicle had been approved four months earlier with forced preconditioning (the vehicle was extremely warmed up prior to the test) in the regular PTI test. The vehicles tested in 2018 with very high NO_x emissions were also approved in the PTI.
In the current PTI four-gas test, the oxidising capacity of a catalytic converter is checked by means of a CO measurement. Measured CO concentrations in a four-gas test were found not to correlate with measured NO_x concentrations. In other words, the CO measurement cannot be used to detect increased NO_x emissions.

The current PTI limit values for lambda are not appropriate:
The window currently permitted in the PTI emission test for the lambda value at increased idling speed ranges from 0.965 to 1.039. It is expected that a tightening of these PTI lambda limit values, in the form of a reduction of this interval, can contribute to the detection of a larger proportion of vehicles with high NO_x emissions.

Improvement of the PTI emission test procedure is expected to be effective for better detection of petrol vehicles with a NO_x emission problem:
The current test procedure of the PTI four-gas test leads in practice to non-uniform test results.

The following aspects, among others, are conceivable to improve the procedure:
- The use of a minimum stabilisation and measurement time.
- The prescription of the measurement frequency.
- Defining the sequence and duration of the tests at high and low idle speeds.
- Setting requirements for the preconditioning of the catalyst (in the current test procedure, minimum requirements are set which do allow non-realistic (excessive) preconditioning.

Cold start stationary tests may be applicable as a screening test:
In idling tests starting with a cold engine and warming up of the three-way catalyst for about 20 minutes at idling speed, the CO, THC and NO_x concentrations decreased by more than 80% in most of the vehicles tested. For some vehicles these reductions were 50 to 80%. Only one vehicle had very low reductions of less than 20%. This warm-up test may be an option for screening of vehicle emissions.

NH_3 emissions are relatively high in urban traffic and vary greatly depending on the type of vehicle:
In the context of nitrogen deposition, it is interesting to know which NH_3 emissions occur from various sources. For this reason, NH_3 emissions have also been measured in this project. The average NH_3 emission of the 38 vehicles tested on the road is 32.1 mg/km and varies from 1 to 99 mg/km per vehicle. In urban traffic the measured average NH_3 emission was 49 mg/km, on rural roads 22 mg/km and on highways 21 mg/km.

Emission factors describe per component (e.g. NO_x, NH_3) an average emission per type of vehicle and type of road and are used for nitrogen deposition and air quality calculations. The currently measured average NH_3 emissions differ from the actual values of NH_3 emission factors which are for urban/off-road/highway 18.8, 19.6 and 35.8 mg/km. The currently measured values are used as input for the annual update of the emission factors for road traffic.

Furthermore, the NH_3 emission of four tested vehicles, after a cold start, appears to be relatively high. In the first 7.2 km these are on average more than four times higher than in the same test with a warm start.

Recommendations:

- Since vehicles with severely defective emission control systems seem to have a major influence on the total emissions of petrol vehicles, it is desirable to obtain more information about the share of these vehicles in the Dutch fleet. Other sources (such as conclusive PTI databases) may provide further insight into the minimum proportion of vehicles with defective emission control systems.

- To allow better detection, in the PTI, of vehicles with high NO_x emissions, a return to the four-gas test (instead of read out of the OBD) is recommended. However, this in combination with an improved test procedure. The advice is to investigate further how exactly the current PTI procedure for the four-gas test can be improved. Several aspects to be taken into account have been identified in this report. Once the detection of vehicles with excessive NO_x emissions has become more feasible, these vehicles can then be repaired or, in the case of an insoluble source of high emissions, possibly disappear from the vehicle fleet.

Closing information

Insight into emission factors at higher mileages

Measured vehicle emission levels are used to establish emission factors. Emissions from petrol vehicles have been measured in the past, these vehicles were only a few years old at the time and still had low mileage. On the basis of these data, emission factors were then drawn up for the various practical situations on the road. The insight now obtained into the emissions of the vehicles tested at higher mileages is valuable information for adjusting the emission factors due to ageing effects.

What were the emissions measured with?

The vehicles have undergone a practical driving cycle on public roads.
PTI emission tests were also carried. The practical test on public roads used a modified version of the Smart Emissions Measurement System (SEMS) from TNO, which provides good indications of NO_x, NH_3 and CO_2 emissions. Validation measurements with test equipment of a roller dynamometer showed that with the adapted measuring system limited deviations in measured CO_2 emissions occurred from +6% to +8% and for NO_x emissions deviations from -10% to -14%.

Contents

1 Introduction

This report presents detailed results of on road emission tests carried out by TNO in the period autumn 2019 - summer 2020. The tests focussed on emissions of in-use, older, petrol vehicles with three-way catalyst and high mileages.
This vehicle group has a significant impact on the total emissions of passenger vehicles after 2020, mainly due to the fact that it concerns still several millions of vehicles in the Netherlands. The emission tests were carried out for the Dutch Ministry of Infrastructure and Water Management.

With this report TNO intends to provide clarity and understanding on the measured data and what the results do and do not imply. TNO and the Dutch Ministry of Infrastructure and Water Management aspire to provide maximum transparency on the information that feeds into policy decisions regarding air quality and emission legislation. Results of the chassis dynamometer measurements with twelve other passenger vehicles were published in an earlier stage [TNO 2018]. However, it was decided to test a larger set of vehicles, on the road. The current report presents the measurement results of this larger set of vehicles.

1.1 Context

Euro emission standards
To minimize air pollutant emissions of light-duty vehicles, in 1992 the European Commission introduced the Euro emission standards. In the course of time, these standards have become more stringent. Currently produced light duty vehicles of categories M and N must comply with the Euro 6b standard. The Euro 6c and 6d-Temp standards, that further limit the emissions, will become mandatory in the period of 2018 - 2020.

The standards apply to vehicles with spark ignition engines and to vehicles with compression ignition engines and cover the following gaseous and particulate emissions:
- CO (carbon monoxide);
- THC (total hydrocarbons);
- NO_x (nitrogen oxides);
- PM (particulate mass),
- PN (particulate number, for direct injection only).

As a result of the Euro emission standards, the pollutant emissions of light-duty vehicles, passenger cars and vans, as observed in type approval tests have reduced significantly over the past decade. However, under real driving conditions some emissions substantially deviate from their type approval values.
The real driving emissions of nitrogen oxides, or NO_x, from diesel vehicles are currently the most important issue with regard to pollutant emissions, as many cities fail to satisfy the NO_2 air-quality standards mainly through the poor real-world performance of diesel cars.[1]

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[1] http://www.platformparticipatie.nl/projecten/alle-projecten/projectenlijst/aanpassing-nationaal-samenwerkingsprogramma-luchtkwaliteit-2018/index.aspx

As NO_x represents the sum of NO and NO_2 emitted, and much of the NO is converted to NO_2 in ambient conditions, reducing NO_x emissions of vehicles is important for bringing down the ambient air NO_2 concentration in cities. In the Netherlands, the ambient NO_2 concentration still exceeds European limits at numerous urban road-side locations[2].

For petrol vehicles, tested by TNO annually till 2008 and more intermittently after that time, limited deviations between the type-approval tests and the real-world tests were observed. The NEDC type-approval test definitions, with the low test velocity, short distance, and the cold start, formed stringent requirements for petrol vehicle technology which ensured in real-world circumstances the emissions were typically lower than the emission limits in the type-approval test.

Moreover, from monitoring programs, such as remote sensing studies, there was little concern on the real-world performance of petrol vehicles. However, given the size of the fleet and, for example, the impact on the total emissions after 2020, there are risks that minor deviations in the estimates will have considerable consequences for the total real-world emissions.

Commissioned by the Dutch Ministry of Infrastructure and Water Management, TNO regularly performs emission measurements within the “in-use compliance programme for light-duty vehicles”. In the early years, i.e., in 1987 to 2000, the focus was on performing a number of standard type approval tests on a large number of vehicles in the lab. In recent years, however, the emphasis has shifted towards gathering emission data under conditions that are more representative for real-world driving, by using various non-standard, i.e., real-world, driving cycles in the lab and by increasingly testing cars on the road with mobile emission measurement equipment.

Emission factors

The emission factors, or average emissions, for pollutant tailpipe emissions of this group of vehicles are typically below the type-approval limit. The 2017 emission factors are given in Table 1-1.

The urban emissions are substantially higher than rural and motorway emissions. This is the result of the cold start contribution. In the total emissions, the start of the cold engine typically dominates the emissions. In the first 300 metres of driving the same emissions are produced as in the next twenty or more kilometres. For urban driving it is estimated that for every 7 kilometres of driving one cold start occurs.[3]

TNO is one of the few institutes in Europe that perform independent emission tests. Based on the results of performed emission tests, TNO develops, and annually updates, Dutch vehicle emission factors that represent the average real-world emissions data for specific various vehicle types categories under different driving and traffic conditions.

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[2] http://www.atlasleefomgeving.nl/en/meer-weten/lucht/stikstofdioxide

[3] See report: CBS Methods for calculating emissions of transport in the Netherlands, 2017.

Table 1-1: Emission factors for Euro-2 to Euro-5 petrol vehicles for the Dutch air-quality assessments of 2017.

road type	g/km	Euro-2	Euro-3	Euro-4	Euro-5
urban	NOx	0.4684	0.1480	0.0539	0.0431
	HC	0.5132	0.4374	0.4197	0.3357
	PM	0.0046	0.0023	0.0023	0.0019
	CO	10.6833	6.6475	5.6150	4.4920
	Elemental Carbon	0.0012	0.0004	0.0004	0.0003
	real-world CO2	284.7	254.6	235.9	213.2
rural	NOx	0.2130	0.0594	0.0248	0.0199
	HC	0.2334	0.2153	0.2118	0.1694
	PM	0.0023	0.0012	0.0012	0.0009
	CO	4.3987	3.2906	2.8732	2.2985
	Elemental Carbon	0.0006	0.0002	0.0002	0.0001
	real-world CO2	143.3	152.6	149.2	134.9
motorway	NOx	0.1984	0.0360	0.0147	0.0117
	HC	0.0654	0.0216	0.0189	0.0151
	PM	0.0050	0.0025	0.0025	0.0025
	CO	3.4073	1.8849	1.6523	1.3218
	Elemental Carbon	0.0013	0.0004	0.0004	0.0004
	real-world CO2	203.0	203.6	194.8	176.1

Vehicle emission factors are used for emission inventories and air quality monitoring. The emission factors, and the underlying test results, are one of the few independent sources of evidence for the growing difference between legislative emission limits and real-world emission performance of cars. Furthermore, the insights obtained in emission measurement programs serve as input for the activities of the Dutch government and the RDW in the context of regulation and legislative processes in Brussels (European Commission) and Geneva (GRPE) to improve emission legislation and the associated test procedures for light duty vehicles, all with the aim to reduce real-world emissions and improve air quality.

Lack of data of older petrol vehicles

With the focus in recent years on diesel vehicles and NO_x emissions, the test programmes for petrol vehicles were limited. With Euro-5 a few incidental and specialized test programmes for petrol vehicles were executed. The test programme in 2016, was intended to determine PM and EC emissions of the emerging GDI technology vehicles. The test program of 2018-2019 was intended to investigate emissions of petrol vehicles with high mileages.

A lack of emission data of older petrol vehicles was identified: Petrol passenger cars have been measured in the past when these vehicles were only a few years old and had limited odometer readings. With the prevalence of petrol cars on the Dutch roads of all ages, they are a major contributor to the emission totals. Even a minor underestimation of petrol vehicle NO_x or NH_3 emission may have significant environmental impact. On the basis of this data, emission factors have been determined for the different practical situations on the road. With increasing age and mileages, the question is whether these vehicles still have the same emission levels.

Because petrol cars are their entire lifespan on the Dutch roads (they are hardly exported, but imported in significant numbers), and because, as they get older, they become a growing share of the total amount of vehicles within cities, they are relevant for urban air quality. It is also the largest group of cars: they constitute more than 70% of all urban traffic. Modern petrol cars reach on average 100,000 kilometres after 7 years [TNO 2015].

A vehicle from 1990 and before had an average lifespan of 18 years or less and 150,000 kilometres. Vehicles from 2005 and earlier reach the 150,000 at 10 years, and likely drive more than 200,000 kilometres in total. Furthermore, a lack of emission data of older vehicles is still the case. Therefore, it was decided to perform an exploratory emission measurement program with petrol passenger cars with high mileages. Also the fact that the Dutch petrol fleet has an increasing age possibly showing deterioration effects of after treatment system parts, is another point of concern and underlines the importance of this study.

1.2 Aim and approach

The aim of the project was to assess the real-world NO_x emission performance of petrol passenger cars with three way catalyst and higher mileages, and to provide suggestions for promising measurement techniques for a periodic test for NO_x emissions from petrol vehicles. This was done by performing emission measurements on the road under real-world conditions and analysis of the collected results. Measurement results are also input for an update of the emission factors for this vehicle category.

This study involves on-road emission measurements on a total of 38 Euro 2, Euro 3, Euro 4, Euro 5 and Euro 6 passenger vehicles. Together with the former twelve petrol vehicles that were tested on the chassis dynamometer this number of vehicles provides a basis to determine trends in their emission behaviour and to indicate average deterioration factors for the different road types.

1.3 TNO policy with respect to publication of data

TNO takes the care in generating data and in communication on the findings of its studies to the various stakeholders. It is beneficial to ensure no errors are made in the testing and problems are addressed early.

In the evaluation and interpretation of test results on individual vehicles the following considerations need to be taken into account:

- The tests performed by TNO are intended to determine the levels and trends of emissions of various categories of vehicles. The tests are not intended for enforcement, and they are not suitable for identifying or claiming fraud or other vehicle-related irregularities in a scientifically and legally watertight way.
- For each make or model, only a single vehicle or a small number of vehicles is/are tested a limited number of times. This means that the results correlate to the specific condition of the tested vehicles or to specific test conditions. The latter is especially the case in real-world testing on the road in which a large number of conditions, that have a strong influence on test results, vary from trip to trip.

In publications about the emission test results on light duty vehicles TNO has up to March 2016, for reasons as indicated above, chosen to present test results in a way that does not allow makes and models to be identified. In case results of individual vehicles were reported, these were always anonymized.

As part of TNO's constructive contribution to the on-going public debate about the real-world NO_x emissions of diesel cars, TNO has decided to present test results with references to makes and models. This decision also meets a desire expressed by the Dutch Ministry of Infrastructure and Water Management.
By presenting results from the complete sample of vehicle models tested, covering a wide range of makes and models, and by providing the necessary background information on test procedures and test conditions as well as caveats with respect to what can be concluded from these data, the test results on individual vehicle models are presented in a context that allows a well-balanced interpretation of the meaning of the results.

Finally, we would like to emphasize that as an independent knowledge institute, TNO is, has been, and will be open to constructive dialogue with industry and governments. This is part of TNO's efforts to work together with relevant stakeholders in finding and supporting the implementation of effective solutions to reduce real-world emissions of harmful substances from vehicles, as well to determine and demonstrate the effects of implemented measures in an objective way.

1.4 Structure of the report

Information regarding the selection and the basic specifications of the selected vehicles can be found in Chapter 2. This chapter also provides detailed information about emission limit values, the used test cycles and the test equipment.
Chapter 3 presents an overview of the test results for the tested vehicles, followed by analyses in chapter 4 and discussions in chapter 5. Conclusions and recommendations for further research are reported in the chapters 6 and 7.
Test results of the individual vehicles as well as the specification of the test equipment as used during the tests are part of the appendices.

2 Test program

This chapter presents the most important characteristics of the on-road test program as performed.

2.1 Selection, origin and mileage validity of the tested vehicles

2.1.1 Vehicle selection

Starting point for the selection of vehicles to be tested was the actual Dutch fleet composition of September 2019. The number of vehicles to be tested within this project was limited to 38. Selection was done in such a way that the test vehicles represent the older vehicles. Most of the selected vehicles belong to the group of highest sales vehicles, were kindly offered by private individuals and generally in private use.

2.1.2 Vehicle properties

In Table 2-1 summarized data of the mileages and ages of the tested vehicles are specified. All vehicles had a first date of registration between 1998 and 2017 and mileages were between 156,663 and 550,384 km. Thirty-two vehicles were privately owned and six vehicles were obtained from two car dealers. More details of the tested vehicles are reported in Appendix B. Figure 2-1 shows the relationship of vehicle age and mileage of the tested vehicles.

Table 2-1: Mileages of tested petrol passenger cars with a three-way catalyst.

Euro class	Number of tested vehicles	Mileage range [km]	Average Mileage [km]	Average Age [year]
1	0	-	-	-
2	8	181,228 – 550,384	283,683	20.9
3	9	177,478 – 370,859	234,298	17.0
4	16	156,663 – 262,826	194,361	14.3
5	4	176,074 – 220,292	197,309	7.1
6	1	175,728	175,728	3.0
Total	38	156,663 – 550,384	222,444	15.8

All tested vehicles were equipped with a three-way catalyst. In 36 vehicles stoichiometric air-fuel mixtures were applied in the full engine map and two vehicles (Toyota Avensis and BMW 320i) were operating with a dual air-fuel strategy (lean burn and stoichiometric). The BMW 320i was also equipped with a Lean NO_x Trap.

Validity of vehicle mileages

The history of the vehicle mileages of the tested vehicles was checked in the Dutch national database of vehicle registrations. Since 2011 all vehicle mileages of regular maintenance activities and periodic technical inspections are stored in this database (see https://ovi.rdw.nl/ or use the RDW vehicle app).

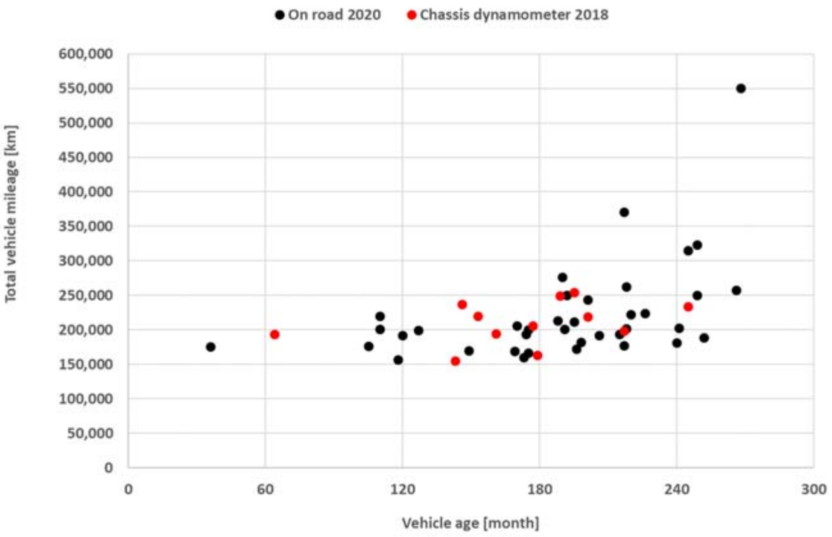

Figure 2-1: Age and odometer readings of the tested vehicles (the 12 vehicles of the chassis dynamometer test program of 2018 are included). Vehicles were selected on the basis of odometer values, and therefore centre around 200,000 kilometres.

Table 2-2 shows the results of the validity checks of the vehicle mileages. Thirty-one vehicles had a vehicle mileage with sense, their consecutive registered mileages have a logic order. Three vehicles were imported and could not be assessed because data were missing. Four vehicles had a vehicle mileage which made no sense with the state of the vehicle. This might be caused in case of an odometer change, incorrect registration or manipulation of the odometer. From the individual mileage registration reports the correct vehicle mileages could be derived.

Table 2-2: Validity of vehicle mileages.

Status vehicle mileage	Number of vehicles	Comment
Plausible	31	-
Implausible	4	Toyota Starlet, Peugeot 206, Renault Megane, Opel Zafira.
Imported vehicle	3	Opel Corsa, VW Golf, BMW 320i
Unknown	-	-
Total	38	

2.2 Emission limit values

2.2.1 European type approval emission limit values

In Table 2-3 the European emission limit values of passenger vehicles and their durability and In Service Conformity mileages are shown. The limit values are based on a New European Driving Cycle (NEDC) with a cold start.

Table 2-3: NEDC Emission limit values of petrol passenger vehicles.

	Emission limit values of M1 Class 1 petrol vehicles								
Emission	**THC**	**NMHC**	**CO**	**NO_x**	**PM**	**HC+ NOx**	**PN**	**Durability limit**	**ISC limit**
Class	**[mg/km]**						**[#/km]**	**[km]**	**[km]**
Euro 1	-	-	2,720	-	-	970	-	80,000	-
Euro 2	-	-	2,200	-	-	500	-	80,000	-
Euro 3	200	-	2,300	150	-	-	-	80,000	-
Euro 4	100	-	1,000	80	-	-	-	100,000	tbr
Euro 5a	100	68	1,000	60	5.0	-	-	160,000	100,000
Euro 5b	100	68	1,000	60	4.5	-	-	160,000	100,000
Euro 6b	100	68	1,000	60	4.5	-	6.0E+12	160,000	100,000
Euro 6c	100	68	1,000	60	4.5	-	6.0E+11	160,000	100,000

For calculation of the conformity factors (CF) of Euro 2 vehicles, the informal NO_x limit value is set at 300 mg/km assuming an informal THC limit value of 200 mg/km.

In this project the definition of the NO_x conformity factor (CF) formula is the NO_x emission of an on road test with warm start [mg/km] divided by the NO_x limit value [mg/km] of an NEDC type approval test with cold start.

2.2.2 *NO_x deterioration factors*

The durability of the vehicle emission performance is characterised with deterioration factors and a mileage. In Table 2-4 the NO_x deterioration factors, mileages and corrected NO_x deterioration factors @ 160,000 km are reported (with the assumption that deterioration is a linear mechanism).

Table 2-4: NO_x limit values incl. durability factors and mileage corrections of positive ignition engines (class M).

Euro class	**Durability Mileage [km]**	**NO_x deterioration factor [-]**	**NO_x limit value w.o. / w deterioration [mg/km]**	**Corrected NO_x limit value Incl. deterioration* [mg/km]**
2	80,000	1.5	‘300’ – 450	600
3	80,000	1.2	150 – 180	210
4	100,000	1.2	80 – 96	106
5	160,000	1.6	60 – 96	96
6	160,000	1.6	60 - 96	96

*Assumed linear deterioration

2.2.3 *European emission limit values for the Periodic Technical Inspection*

The European Directive 2014/45/EC and the Dutch vehicle regulation (Wegenverkeerswet, Regeling Voertuigen) for periodic technical inspections (PTI) describe a similar PTI emission test procedure. For petrol vehicles with a three way catalyst the warmed up engine is tested at low- and high idle speed and CO, CO_2, THC and O_2 concentrations are measured in the tailpipe and the actual lambda value is calculated. In Table 2-5 the CO emission limit values and the range of allowed lambda values for low and high idle speed tests are reported.

Table 2-5: European PTI emission limit values for petrol vehicles (Source 2014/45/EU).

Low idle speed warm engine						
Registration date		Emission class		CO	Lambda	Lambda
From	To				min	max
				[vol%]	[-]	[-]
1-1-1974	30-9-1986	15.03		4.5	-	-
1-10-1986	30-6-2002	15.04		3.5	-	-
1-1-1986	30-6-2002	Euro 1,2	Catalyst + lambda sensor	0.5	-	-
1-7-2002	>	Euro 3,4,5,6		0.3	-	-
high idle speed 2000 - 3200 rpm						
Registration date		Emission class		CO	Lambda	Lambda
From	To				min	max
				[vol%]	[-]	[-]
1-1-1974	30-9-1986	15.03		-	-	-
1-10-1986	30-6-2002	15.04		-	-	-
1-1-1993	30-6-2002	Euro 1,2	Catalyst + lambda sensor	0.3	0.97	1.03
1-7-2002	>	Euro 3,4,5,6		0.2	0.97	1.03

2.3 Test equipment

2.3.1 *Mobile Emission Measurement System (MEMS)*

In order to be able to screen vehicle emissions on the road with different vehicle bodies a dedicated mobile emission measurement system (MEMS) was developed, see Figure 2-2, Figure 2-3 and Figure 2-4. This test set up, an adapted version of the SEMS measurement system, and the data processing steps are specified in Appendix A. Emission test results are based on exhaust mass flow measurements (pitot tube) and the signals of the GPS, lambda, NO_x-O_2 and NH_3 sensors.
In addition, an automotive 5-gas tester, measuring CO, CO_2, C_6H_{14}, NO_x and O_2 concentrations of undiluted exhaust gas, was installed in the trunk. Furthermore OBD data were logged (if available). A bicycle carrier provided a practical approach for quick assembly and disassembly suited for almost all vehicle makes and bodies.

Figure 2-2: Vehicle with test equipment.

Figure 2-3: Flow measuring tube with dilution air pump and lambda, NO_x-O_2 and NH_3 sensors.

Figure 2-4: Automotive 5-gas tester, 12V battery, 12/24 V DC-convertor, pressure sensor box for a pitot tube and SEMS data logger in the trunk.

In Appendix B the results of the validation of MEMS are reported.

2.4 Test procedure

In this study the vehicles were subjected to a defined test procedure that contains the next steps:

1. Vehicle registration.
2. Vehicle inspection and validation check of the mileage.
3. Vehicle preparation.
4. Installation and commissioning of test equipment.
5. Idle speed tests and warming up of the engine.
6. On road emission test of 50 km (see Figure 2-5).
7. Idle speed tests.
8. Data processing.
9. Determination of pass/fail.
10. In case of a pass the test procedure is terminated.
11. In case of a fail the vehicle may be repaired and the test procedure repeated, starting at step 5.

Undiluted exhaust gas was sampled in PTI and on road tests with a 5-gas tester (CO, CO_2, C_6H_{14}, O_2 and NO_x) with a sample rate of 4 Hz.

2.4.1 *Vehicle inspection and preparation*

After receival the vehicles were inspected and prepared as follows:

a. Registration of maintenance history (if available)
b. Leak check of the exhaust system.
c. Registration of active OBD fault codes, if any.
d. Installation of the Mobile Emission Measurement System (MEMS)
e. Commissioning of the test set up in a short road trip of 5 km.

2.4.2 *Applied fuels:*

In Table 2-6 the applied test fuels of the test program are specified.

Table 2-6: Applied EN 228 test fuels

Type		1	2
Quality		Trade E10	Trade E5
RON	[-]	95	98
Ethanol content	[vol%]	< 10	< 5

2.4.3 *Applied emission test procedure*

All vehicles were tested in the technical condition ‘as received’ and subjected to the next test emission test program:

1. Low idle speed test with cold engine start and warming up at low idle speed.
2. High and low idle speed test with a warm engine.
3. On road test of 48-51 km with a warm engine start (urban, rural, motorway).
4. High and low idle speed test with a warm engine.

In Figure 2-5 the speed profile of the on road test is shown. Due to actual traffic conditions the profile may deviate slightly from test to test.

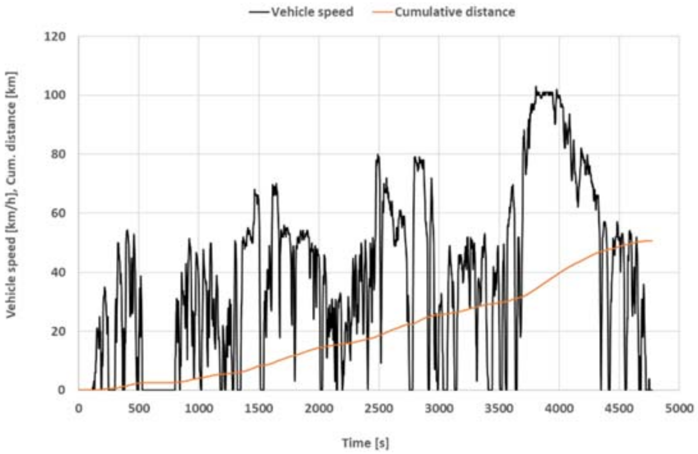

Figure 2-5: Example of an on-road test trip of 50.8 km with urban 19.4 km, rural 20.8 km and motorway 10.6 km use. The average vehicle speed in this test is 38.6 km/h.

3 Test results

The emission tests were performed between December 2019 and September 2020. In the following sections the validation of MEMS and the overall test results are reported. Detailed test results are reported in appendices B, C and D.

3.1 Summary on road emission test results

3.1.1 Overview average emission test results of 38 tested vehicles.

After the warming up test at idle speed every vehicle was subjected to an on-road emission test with a length of 48-50 km.

In Table 3-1 an overview of the average emission test results of the 38 tested petrol vehicles is given.

- The measured on road NO_x emission of 38 tested vehicles is in the range of 17 to 1,267 mg/km and on average 166.4 mg/km. The conformity factors are in the range of 0.2 to 4.7 and on average 1.21. The measured on road CO_2 emission of 38 tested vehicles is in the range of 111 to 217 g/km and on average 164.3 g/km. It must be noted that the emission limit is based on a cold start NEDC test. Warm engine emissions, with functioning emission control are expected to be less than half of the limit.
- The measured NH_3 emission of 38 tested vehicles is in the range of 1 to 99 mg/km and on average 32.1 mg/km.

Table 3-1: Overview average on road emission test results of 38 petrol vehicles with high mileages

	Mileage	**CO_2**	**NO_x**	**NH_3**
	[km * 1,000]	**[g/km]**	**[mg/km]**	**[mg/km]**
Range	157 - 550	111 - 217	17 - 1267	1 - 99
Average	222.4	164.3	166.4	32.1
St. deviation	71.3	26.7	207.2	23.6

Detailed test results of individual vehicles are reported in Appendix A and sorted results in the next sections.

In Table 3-2 the average on-road emission test results are sorted per Euro class. For every Euro class the spread in NO_x and NH_3 emission is large.
Detailed test results of individual vehicles are reported in Appendix A and sorted results in the next sections.

Table 3-2: On-road average emission test results (NO_x, NH_3 and CO_2) of 38 tested vehicles sorted per Euro class.

		Euro 2	**Euro 3**	**Euro 4**	**Euro 5**	**Euro 6**
No of vehicles	[-]	8	9	16	4	1
Av. age	[year]	20.9	17.0	15.0	9.3	3.0
Av. mileage	[km*1000]	284	234	194	197	176
Av. empty mass	[kg]	1159	1169	1172	1234	1011
NOx						
NEDC limit value	[mg/km]	300*	150	80	60	60
Average	[mg/km]	382	140	95	113	35
St. deviation	[mg/km]	340	103	71	100	-
Minimum	[mg/km]	163	43	17	44	-
Maximum	[mg/km]	1267	352	264	284	-
NH_3						
Average	[mg/km]	40	23	27	58	20
St. deviation	[mg/km]	26	12	21	26	-
Minimum	[mg/km]	10	5	1	12	-
Maximum	[mg/km]	99	38	85	77	-
CO_2						
Average	[mg/km]	166	166	170	145	111
St. deviation	[mg/km]	24	18	29	14	-
Minimum	[mg/km]	135	141	121	125	-
Maximum	[mg/km]	209	198	217	160	-

*Derived from HC+NO_x limit value of 500 mg/km.

3.1.2 *NO_x emissions*

In Figure 3-1 the average on road NO_x emissions of all tested vehicles and in Figure 3-2 the NO_x conformity factors are shown. One vehicle had a very high NO_x emission of 1267 mg/km.

The NO_x conformity factors of the tested vehicles are in the range of 0.4 – 4.7 and on average 1,21. The NO_x emissions as well as the NO_x conformity factors have a large spread and are not correlated with vehicle mileage (> 160.000 km).

In Figure 3-3 the average NO_x emissions of the tested vehicles are sorted per Euro class. The vehicle with a mileage of 550,000 km was a VW Passat (Euro 2) with a second three-way catalyst which was mounted at a mileage of 359,975 km. In every Euro class with multiple vehicles there is a large spread of NO_x emission. The NO_x emissions of the tested vehicles are not correlated with Euro class.

In section 4.1 a detailed analysis of the NO_x emissions of all vehicles and the conclusions are reported.

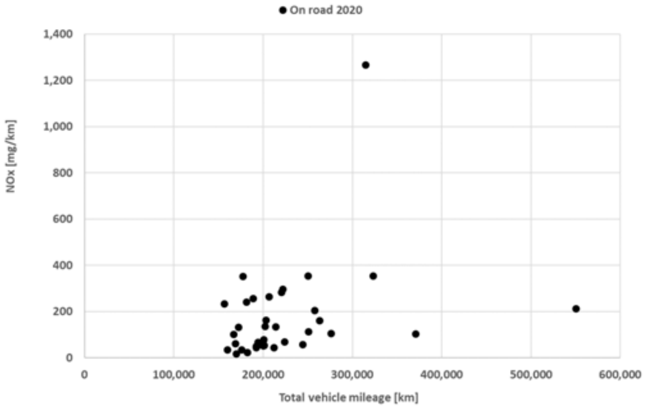

Figure 3-1: Average on road NO_x emission as function of the mileage of 38 petrol vehicles.

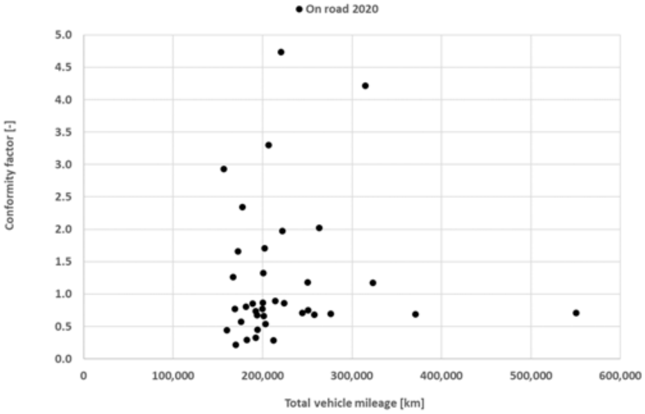

Figure 3-2: NO_x conformity factors as function of odometer readings of 38 petrol vehicles.

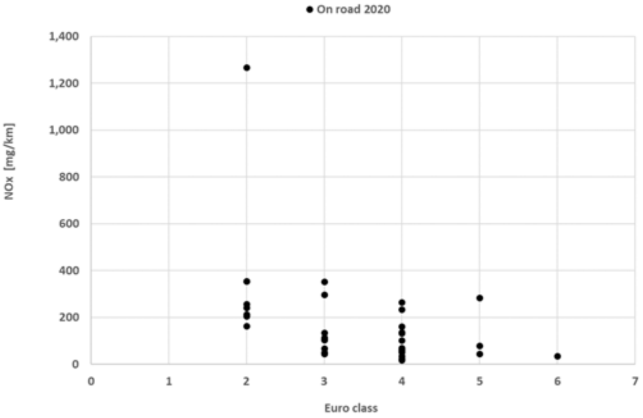

Figure 3-3: Average on road NO_x emissions as function of Euro class of 38 petrol vehicles.

3.1.3 NH_3 emissions

In Figure 3-4 the average on road NH_3 emissions as a function of vehicle mileage of the tested vehicles and in Figure 3-5 the NH_3 emissions as a function of vehicle age are shown. The measured on road average NH_3 emission of 38 tested vehicles is in the range of 1 to 99 mg/km and on average 32.1 mg/km.
The NH_3 emissions of the tested vehicles are not correlated with vehicle age or mileage.

In Figure 3-6 the average NH_3 emissions of the tested vehicles are sorted per emission class. For every Euro class with multiple tested vehicles there is a large spread of NH_3 emission and they are not correlated.

In section 4.7 a more detailed analysis of the NH_3 emissions and conclusions are reported.

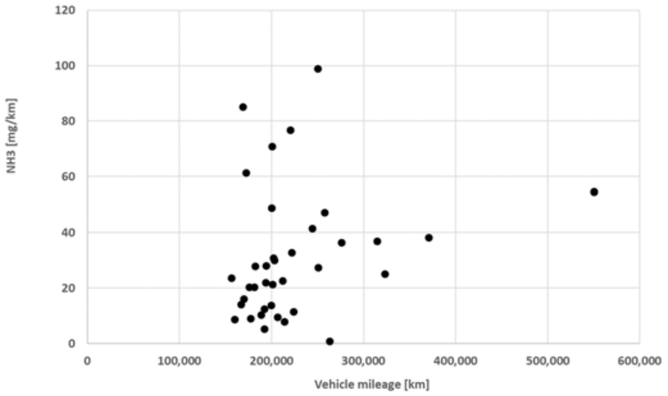

Figure 3-4: Average NH_3 emissions of road tests as function of the mileages of 38 petrol vehicles.

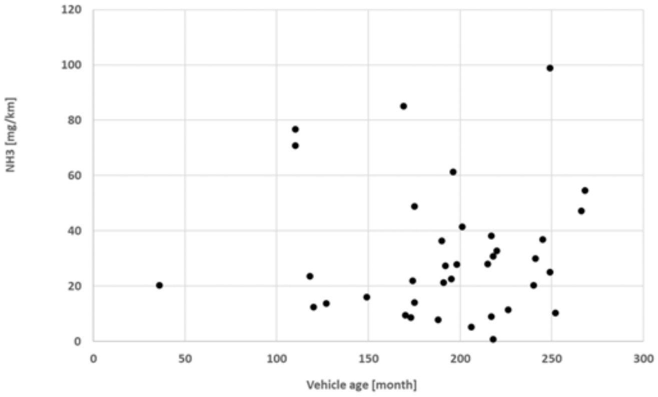

Figure 3-5: : Average on-road NH_3 emissions as function of vehicle age of 38 petrol vehicles.

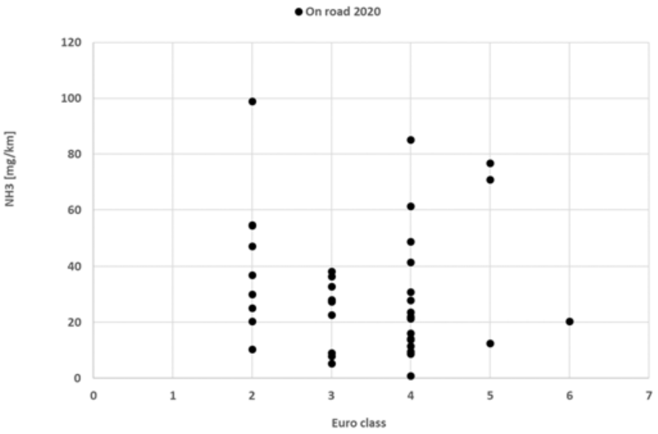

Figure 3-6: Average on road NH_3 emissions as function of Euro class of 38 petrol vehicles.

3.2 PTI emission test results

After execution of the on road emission test, so with a warm motor, PTI emission tests at low and high idle speed were performed. In Figure 3-7 the measured CO emission at low idle speed of the tested vehicles is shown. Except for two vehicles, all measured CO concentrations at low idle speed are less than 0.30 vol%. Vehicles with deviating CO concentrations were retested and the CO concentration in a second test was less than 0.30 vol%. These vehicles had an irregular emission behaviour because the air-fuel control (lambda) of the engine was not stable.

The four vehicles with higher lambda values (1.01, 1.03 and 1.08) at low idle speed had exhaust system leakages (flange not tight or muffler leakage), despite earlier visual inspections. After repair the lambda values were 0.99 and 1.00.

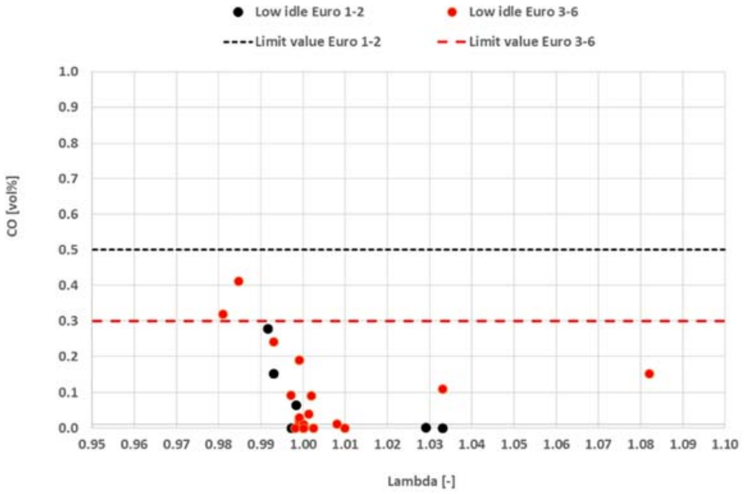

Figure 3-7: CO concentrations as function of lambda of 38 gasoline vehicles at low idle speed.

The measured CO concentration at high idle speed of the tested vehicles is shown in Figure 3-8. The CO concentration of all tested Euro 3, 4, 5 and 6 vehicles at high idle speed is below the PTI limit value of 0.2 vol%.

Two Euro 2 vehicles exceeded the CO limit value of 0.3 vol%. The Renault Clio was retested and the CO emission was not stable and sometimes less than 0.30 vol%. For the Euro 2 Peugeot 206 the CO concentration stayed above the limit value of 0.30 vol%.

All vehicles operated at high idle speed in the required lambda window of 0.97 to 1.03. Lambda at high idle speed of most vehicles is in the range of 0.99 to 1.00. The three vehicles with higher lambda values at high idle speed had an exhaust system leakage or worn three-way catalyst.

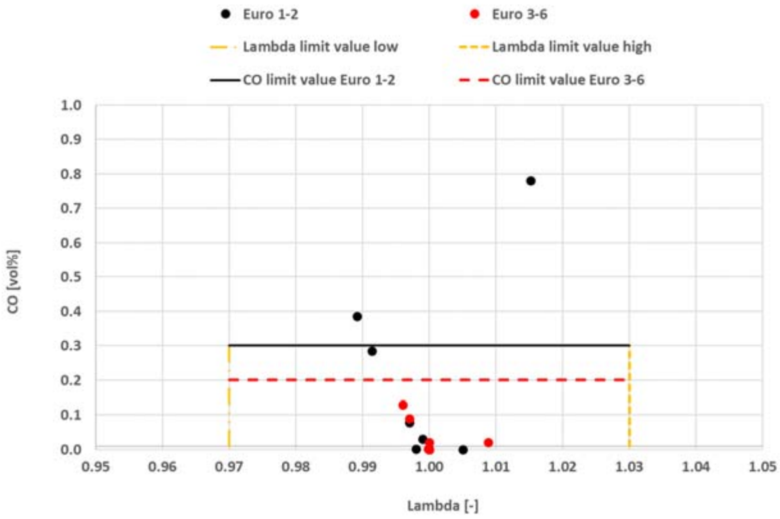

Figure 3-8: CO concentrations and lambda values of 38 gasoline vehicles at high idle speed.

In the executed PTI's on top of the regular emission test, more data were measured/determined. In Figure 3-9 the results of the executed PTI tests of all 38 tested vehicles and the on-road NO_x classification (medium or high emitter) are reported. When a colour pops up the specific test fails or specific criteria were met and with a blank the specific test had a pass.

The specific PTI fail criteria were:

- MIL is burning (yellow).
- Engine and emission related OBD codes are active (grey).
- CO concentration at low or high idle speed is too high (black).
- Lambda at high idle speed is out of range (< 0.965 or > 1.039) (purple).
- NO_x concentration at low idle speed > 50 ppm (light blue).
- NO_x concentration at high idle speed > 150 ppm (dark blue).
- Medium NO_x emitter, CF > 2 and NO_x < 750 mg/km (orange).
- High NO_x emitter, CF > 4 and NO_x > 750 mg/km (red).

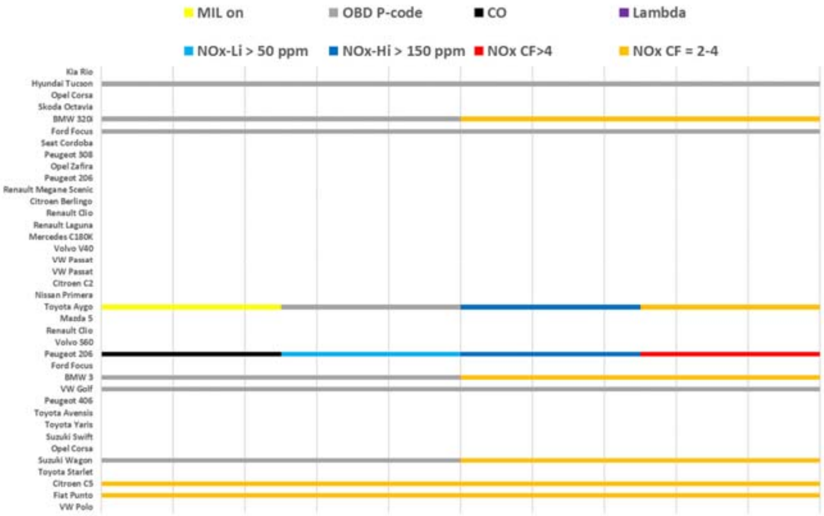

Figure 3-9: PTI parameters and emission characteristics of the 38 tested vehicles (x-axis has no meaning).

Ten vehicles had one or more failures or elevated emissions, these are:

- Fiat Punto: NO_x = 235 mg/km (CF = 2.9). Nothing was detected in PTI tests
- Citroen C5: NO_x = 352 mg/km (CF = 2.3). Nothing was detected in PTI tests.
- Suzuki Wagon: NO_x 296 mg/km (CF = 2.0). Active OBD codes P0130 and P0400.
- VW Golf: NO_x 355 mg/km (CF = 1.2). Active OBD codes 17840 and 17538.
- BMW 3: NO_x 162 mg/km (CF = 2.0). Active OBD codes: 2854, 2783 and 2865.
- Peugeot 206: NO_x 1267 mg/km (‘CF = 4.2’). CO and NO_x at idle speed > 150 ppm.
- Toyota Aygo: NO_x 264 mg/km (CF = 3.3). MIL on. OBD code P0420 active and NO_x at high idle speed > 150 ppm.
- Ford Focus Euro 4: Active OBD code P000A active.
- BMW 320i: NO_x = 284 mg/km (CF = 4.7). Active OBD code 30EA.
- Hyundai Tucson: NO_x = 62 mg/km (CF = 0.8) Active OBD codes P0011 and P0016.

High emitter:
The Euro 2 Peugeot 206 (without OBD system) with an average on-road NO_x emission of 1267 mg/km did not meet the Dutch PTI emission criteria because the CO concentration at high idle speed was 0.41 – 0.88 vol% and higher than the effective limit value of 0.39 vol%. An additional measurement of the NO_x concentration at idle speeds indicated high values (NO_x @ low idle speed > 50 ppm and at high idle speed > 150 ppm).

Medium emitters:
Six vehicles with an elevated NO_x emission (CF = 2 – 4) passed the Dutch PTI. From these vehicles the MIL of the Toyota Aygo (CF = 3.3) was on and this vehicle had an active OBD emission code; the NO_x concentration at high idle speed was more than 150 ppm.

The Suzuki Wagon (CF = 2.0) and the BMW 3 (CF = 2.0) had active OBD emission codes. The residual three vehicles (Fiat Punto, Citroen C5 and BMW 320 i) with elevated NO_x emission passed the PTI without any reporting of the OBD system.

Low emitters: Three out of 28 vehicles with a regular NO_x emission (CF < 2) had active OBD emission codes.

3.3 State of maintenance of the tested vehicles

In The Netherlands the registration of the maintenance history of a vehicle is not mandatory. From most tested vehicles the maintenance file (a booklet) was stored in the vehicle and (partially) completed. In addition all vehicle owners were requested to deliver maintenance data and information.

In Table 3-3 a summary of the documented state of maintenance of all vehicles is shown. All tested vehicles passed the mandatory periodic technical inspection in the last 12 months before emission testing. During the lifetime of 19 vehicles all required maintenance activities were executed (documents were complete and up to date). From 11 vehicles maintenance activities were partly registered and 8 vehicles had no maintenance file.

Table 3-3: Maintenance history of the tested vehicles.

Documented state of maintenance	**Number of vehicles**
No data	8
Partly documented	11
Fully documented	19

The documentation of the maintenance history of 50% of the on-road tested vehicles was complete, 29% of the vehicles had a partial documented maintenance history and 21% of the vehicles had no maintenance history documentation

3.4 On Board Diagnostic data

As part of the vehicle inspection the vehicle OBD system was read out. The OBD tests were performed before the execution of the on-road emission test programme of the vehicles. In Table 3-4 the OBD and MIL status of the tested vehicles are reported.

Table 3-4: Overview diagnostic test results of petrol vehicles as received and tested.

Total number of tested vehicles	38
Number of vehicles without OBD system	5
Number of vehicles without active emission OBD fault codes	27
Number of vehicles with active emission OBD fault codes	7
Number of vehicles with burning MIL	1

In Table 3-5 the registered OBD codes and MIL status of the individual vehicle are reported.

Table 3-5: OBD details of vehicles with active OBD codes and MIL status.

Vehicle	**Emission related OBD fault code**
Suzuki Wagon R+	P0400 EGR system, P0130 Lambda sensor
VW Golf	17840 Banks 1 & 2 too lean, 17835 Idle emission not stable
Toyota Aygo	P0420, Catalyst system efficiency below threshold bank 1. MIL on.
BMW 3	2854 variable valve gear, sensor plausibility. 2783 hot-film air mass flow sensor 2865 variable valve gear, power limitation in limp home operating mode
Ford Focus Euro 4	P000A Position of camshaft slow reaction
BMW 320i	P30EA, DeNox catalytic converter, sulphurised
Hyundai Tucson	P011, P016, Camshaft and crankshaft positions

3.5 Three-way catalyst performances in cold and warm condition

3.5.1 *Emissions at idle speed during warming up*

At the start of every test program the three-way catalyst emission performance was investigated in a warming up test at idle speeds. After having reached the light off temperature the CO, C_6H_{14} or NO_x conversion starts and can be flawless at higher operating temperatures. Typically first the CO conversion is completed, sometime later followed by NO_x conversion and it ends with C_6H_{14} conversion.
Catalyst deterioration typically shows longer warming up times and imperfect conversions. Inactive or worn catalysts are not able to convert the three elements CO, C_6H_{14} or NO_x.

In Figure 3-10, Figure 3-11 and Figure 3-12 examples of warming up tests of the next three different vehicles are shown:

Figure 3-10 Mercedes C180 Euro 4 @ 193,458 km with well working catalyst.
Figure 3-11 Peugeot 206 Euro 3 @ 250,611 km with normal deteriorated catalyst.
Figure 3-12 Peugeot 206 Euro 2 @ 314,852 km with defective catalyst.

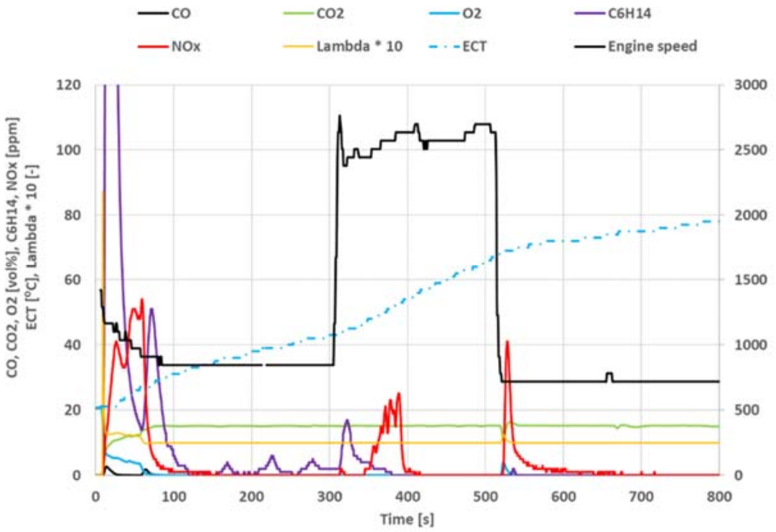

Figure 3-10: Warming up test of a Mercedes C180 (Euro 4) @ 193,458 km at low and high idle speeds (after cold start). Within 100-120 seconds CO, NO_x and C_6H_{14} concentrations reduce towards zero.

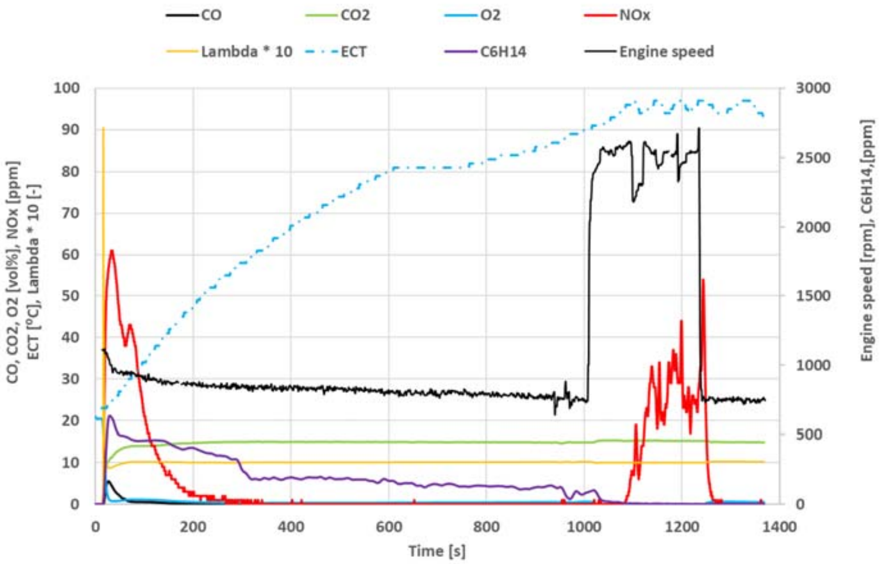

Figure 3-11: Warming up test of a Peugeot 206 (Euro 3) @ 250,611 km at low and high idle speeds (after cold start). CO and NO_x concentrations reduce near zero within 240 and 300 s seconds and the C_6H_{14} concentration is near zero at 1280 seconds after the warming up at high idle speed.

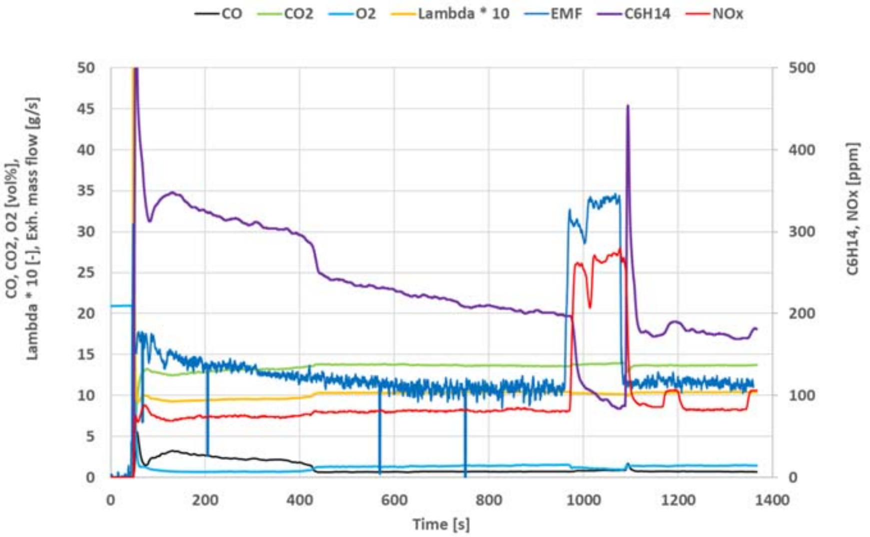

Figure 3-12: Warming up test of a Peugeot 206 (Euro 2) @ 314,852 km with defective three-way catalyst at low and high idle speeds (after cold start). CO and NOx concentrations at low idle speed are 0.71 vol% and 82 ppm. The C_6H_{14} concentration reduces during the warming up from 350 to 170 ppm.

In Table 3-6 the rate of emission reduction (cold versus warmed up catalyst) and the stabilization (or activating) times of the three vehicles are reported. Catalyst deterioration is measured by lower reduction rates and longer stabilization times.

Table 3-6: Rate of emission reduction cold versus warm engine at low idle speed.

Vehicle	**Stabilization time [s]**			**Reduction rate [%]**		
	CO	**C_6H_{14}**	**NO_x**	**CO**	**C_6H_{14}**	**NO_x**
Mercedes C180 Euro 4	120	120	100	100	100	100
Peugeot 206 Euro 3	240	1280	300	95	75	100
Peugeot 206 Euro 2	1200	1200	1200	0	19	11

In addition the emission reduction rates of the low idle speed tests were calculated on the basis of the measured emission concentrations (Conc). The definition of the emission reduction rate is:

Emission reduction rate = 1 - Conc @ warm engine / Conc @ cold engine

In Figure 3-13, Figure 3-14 and Figure 3-15 the CO, C_6H_{14} and NO_x reduction rates of all tested vehicles measured during the warming up of the three-way catalysts are shown. Except one vehicle the reduction rates are above 40% but most are above 80%. The CO, C_6H_{14} and NO_x reduction rates of the three-way catalyst of the Euro 2 Peugeot 206 were 0%, 20% and 10%.

Some vehicles had a decreased CO reduction rate at low idle speed.
This was mainly caused by relative rich air-fuel mixtures (lambda < 0.985).
In idle speed tests with a cold start followed by a warming up of approximately 20 minutes at low idle speed the CO, THC and NO_x reduction rates (based on the measured concentrations) of the majority of the tested vehicles is above 80%. For some vehicles this reduction rate was 50 – 80%. Only one vehicle had a very low emission reduction rate of 0-20%.

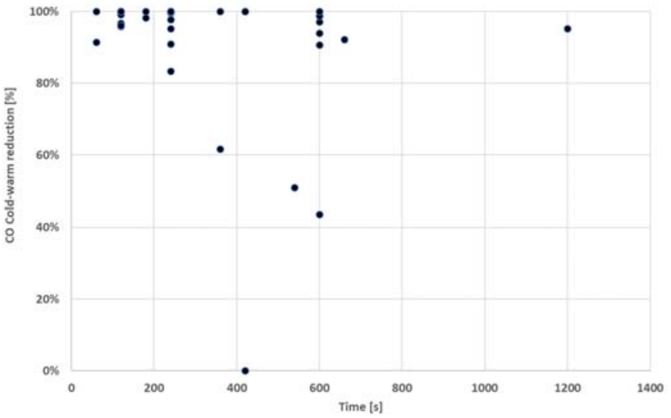

Figure 3-13: CO reduction rates at low idle speed during warming up.

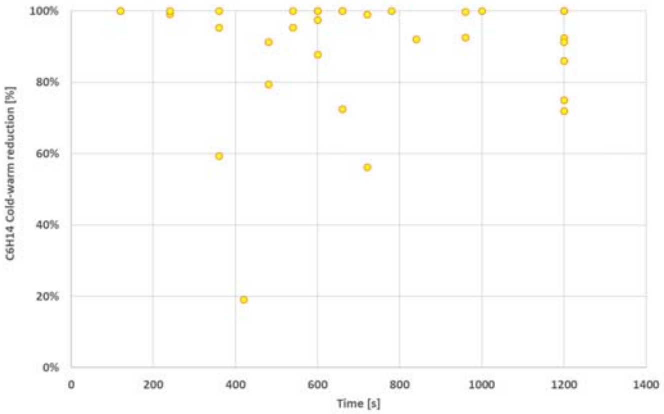

Figure 3-14: C_6H_{14} reduction rates at low idle speed during warming up

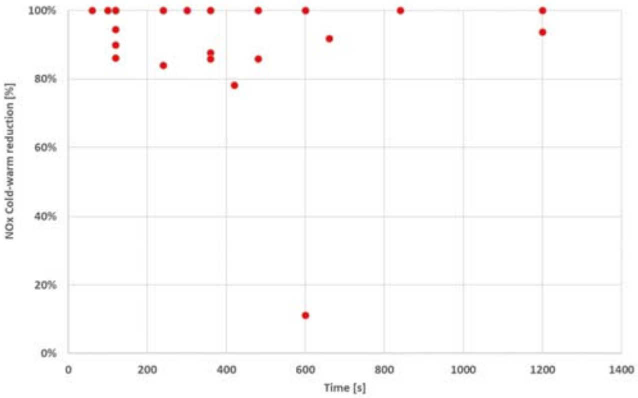

Figure 3-15: NO_x reduction rates at low idle speed during warming up.

3.5.2 *On road tests with cold and warm start*

In Table 3-7 the on road CO_2, NO_x and NH_3 emission test results with cold and warm start of four different vehicles are reported.

For three tested vehicles the CO_2 emission in tests with cold start is 6 to 10% higher than with warm start. For the Citroen C2 the CO_2 emission of the test with warm start was 11% higher than with cold start.

For the Volvo S60 the NO_x emission of the tests with cold start is higher than with warm start, for the Mazda 5 there is no difference and surprisingly the average cold start NO_x emission of the VW Polo and Citroen C2 is lower than with warm start.

Table 3-7: On road emission test results with cold and warm engine start (road trip of 48-50 km).

Vehicle	**CO_2**	**NO_x**	**NH_3**	**CO_2**	**NO_x**	**NH_3**
	[g/km]	**[mg/km]**	**[mg/km]**	**[g/km]**	**[mg/km]**	**[mg/km]**
	Cold start			**Warm start**		
VW Polo	130.9	37.9	21.0	114.3	46.9	15.3
Volvo S60	198.5	158.3	48.8	180.4	103.2	38.3
Mazda 5	188.3	36.2	27.6	176.5	35.5	8.7
Citroen C2	148.4	86.3	10.4	155.3	134.0	7.9

Further analysis of NO_x emissions with cold and warm start is executed in section 4.4.

3.5.3 *Emissions with different driving styles*

Four vehicles were tested with a regular and a sportive driving style; In Table 3-8 the average CO_2, NO_x and NH_3 test results of two vehicles are reported.
With a sportive driving style the measured CO_2 emissions were 6 to 18 % higher, the NO_x emission was 19 to 260 % higher and the NH_3 emission was 2 to 88 % higher than with a regular driving style.

Table 3-8: Average on road emission test results with regular and sportive driving styles.

Vehicle	**CO_2**	**NO_x**	**NH_3**	**CO_2**	**NO_x**	**NH_3**
	[g/km]	**[mg/km]**	**[mg/km]**	**[g/km]**	**[mg/km]**	**[mg/km]**
	Regular			**Sportive**		
Ford Focus	143.1	241.9	20.3	168.9	313.1	24.5
Citroen C2	155.3	134.0	7.9	182.5	159.7	11.4
Opel Corsa	158.3	17.4	16.1	174.7	62.7	16.4
Hyundai Tucson	205.2	62.1	13.8	217.9	109.6	25.9

3.6 Effects of vehicle repairs on emission levels

In order to investigate the effect of vehicle repairs four tested vehicles with elevated NO_x emissions or active OBD failure codes were diagnosed by one of the associated dealers. It was decided to carry out defined repairs and after repair the vehicles were retested on the road. In this section detailed information and analysis of the repairs and emission test results are presented and discussed.

3.6.1 *Summary vehicle repairs*

The NO_x reductions of these repaired vehicles are summarized in Table 3-9. Three repairs resulted in a substantial on-road NO_x reduction of 37 – 93%. The exchange of the lambda sensors of the fourth vehicle (Fiat Punto) didn't reduce the on-road NO_x emission, probably the elevated NO_x emission was caused by deterioration of the catalyst (which was not exchanged).

With current Dutch PTI emission test procedures and criteria the Suzuki Wagon and Toyota Aygo pass. With excessive preconditioning the Peugeot 206 with worn catalyst probably also passes the PTI emission test. The elevated NO_x emission of the Fiat Punto (CF 3.0) cannot be detected with OBD information or the current PTI emission test.

Table 3-9: NO_x reduction of four repaired petrol vehicles.

Vehicle	**NO_x as received**	**NO_x after repair**	**NO_x reduction**
	[mg/km]	**[mg/km]**	**[%]**
Suzuki Wagon R	297	187	37
Fiat Punto	256	250	2
Peugeot 206	1267	87	93
Toyota Aygo	264	20	92

3.6.2 Details of the four repaired vehicles

3.6.2.1 Fiat Grande Punto Euro 4 @ 156,604 km.

At first the Fiat Grande Punto was tested in two on-road tests in the condition as received. In a next stage, six months later, two new lambda sensors (pre and post catalyst) were installed because the lambda values seemed to deviate slightly (too lean mixture) and the vehicle was retested.

Results OBD diagnose and PTI emission tests:
Upon receipt of the vehicle no OBD codes were active and the PTO CO concentrations were well below the limit vales at lambda 1.00.

Emission test results before and after repairs:
In Table 3-10 an overview of the executed on road test results is given.
In the received vehicle condition without OBD fault codes the measured emission in the two on-road tests with an average ambient temperature of 6 and 8 ºC was: CO_2 145.7 and 151.3 g/km, NO_x 277.8 and 234.5 mg/km and NH_3 25.5 and 23.7 mg/km. The measured CO concentration al low idle speed was 0.18 vol% (@ lambda 1.00). At high idle speed the measured lambda was 1.00 and the CO concentration was 0.12 vol%. With these PTI emissions the vehicle passes the PTI test.

Results of the retest, after replacement of the lambda sensors: The measured emission in the two on-road tests with an average ambient temperature of 6 and 8 ºC was: CO_2 143.4 and 145.3 g/km, NO_x 229.4 and 270.7 mg/km and NH_3 21.0 and 24.5 mg/km. The measured CO concentration al low idle speed was 0.33 vol% (@ lambda 1.01). At high idle speed the measured lambda was 1.00 and the CO concentration was 0.15 vol%. With these PTI emissions the vehicle passes the PTI test.

Table 3-10: On road test results of the Fiat Grande Punto (Euro 4 @ 156,604 – 163,798 km) with old and new lambda sensors.

	Dist.	**Tamb.**	**Av. speed**	**CO_2**	**NO_x**	**NH_3**
Vehicle condition	**[km]**	**[ºC]**	**[km/h]**	**[g/km]**	**[mg/km]**	**[mg/km]**
Used lambda sensors 1	48.4	6.0	35.5	145.7	277.8	25.5
Used lambda sensors 2	48.4	7.8	32.9	151.3	234.5	23.7
New lambda sensors 1	49.5	22.0	39.1	143.4	229.4	21.0
New lambda sensors 2	49.3	18.0	41.7	145.3	270.7	24.5

Effect of repairs on the NO_x emission of the Fiat Grande Punto:
The measured on-road NO_x emission of the Fiat Grande Punto with used lambda sensors was on average 256 mg/km and the NO_x emission of the vehicle with new lambda sensors was on average 250 mg/km. In the on road emission tests with used and new lambda sensors the NO_x emission was on a similar level.

In Table 3-11 the PTI 4-gas tests results of the Fiat Punto are reported.
The vehicle passed in all PTI tests the CO and lambda emission criteria. The NO_x concentrations at low and high idle speed were significantly lower with new lambda sensors (at low idle speed 136 and 9 ppm versus 11 and 1 ppm and at high idle speed 59 and 106 ppm versus 5 and 7 ppm).

Table 3-11: PTI test results of the Fiat Grande Punto (Euro 4 @ 156,604 – 163,798 km) with old and new lambda sensors.

	Low idle speed			High idle speed		
	CO	NO_x	Lambda	CO	NO_x	Lambda
Vehicle condition	[vol%]	[ppm]	[-]	[vol%]	[ppm]	[-]
Used lambda sensors 1	0.21	136	0.993	0.04	59	0.993
Used lambda sensors 2	0.10	9	1.001	0.12	106	0.996
New lambda sensors 1	0.35	11	1.005	0.15	5	0.998
New lambda sensors 2	0.31	1	1.006	0.15	7	0.998

Conclusion of repairs of the Fiat Grande Punto:
The elevated NO_x emission of the Fiat Grande Punto was investigated and the vehicle was tested with old and new lambda sensors. With old and new lambda sensors the on road NO_x emission was on average similar (256 versus 250 mg/km). From these results it can be concluded that the elevated NO_x emission of the Fiat Grande Punto was not caused by defective lambda sensors.

Furthermore, the measured NO_x concentration at low and high idle speeds with new lambda sensors was on average significantly lower than with old lambda sensors (73 versus 6 ppm and 83 versus 6 ppm).
The fact that installation of two new lambda sensors resulted in unchanged on road NO_x emissions and lower NO_x concentrations at idle speeds indicates that on road NO_x emissions of petrol vehicles are not related to the NO_x concentrations at low and high idle speed.

Additional analysis NO_x emissions of the Fiat Grande Punto:
The Fiat Grande Punto is not equipped with an EGR-system so NO_x control is mainly done by the three-way catalyst. Because the elevated NO_x emission is not caused by a defective lambda sensor, degradation of the performance of the three-way catalyst is likely the cause, however this was not further investigated.

3.6.2.2 *Suzuki Wagon R+ Euro 3 @ 222,134 km*

Upon receipt of the vehicle, OBD codes P0130 (lambda sensor) and P0400 (EGR-system) appeared to be active. At first the Suzuki Wagon R+ was tested in this received condition. The measured lambda at low idle speed was 1.14. After a cold start and with accelerations the vehicle smoked heavily, white and blue plumes were emitted.

In order to understand the effect on emissions of the pending OBD codes, the vehicle was offered to the Suzuki dealer and the EGR valve was repaired after which the vehicle was retested. In a second repair round, the intake and exhaust systems were repaired and in this condition the vehicle was tested on the road again.

Emission test results before and after repairs:
In Table 3-12 and Table 3-13 an overview of the test results is given.
With the two active OBD fault codes the measured emission in the on-road test with an average ambient temperature of 8.5 ºC was: CO_2 140.7 g/km, NO_x 296.2 mg/km and NH_3 32.8 mg/km. The measured lambda al low idle speed was 1.09. At high idle speed the measured lambda was 1.01 and the CO concentration was 0.02 %. With these PTI emissions the vehicle passed the PTI emission test.

After repair of the blocked EGR valve actuator the measured emissions in the on-road test with an average ambient temperature of 14 ºC were: CO_2 126.7 g/km, NO_x 229.8 mg/km and NH_3 34.1 mg/km. OBD code P0400 was not active anymore. However, lambda at low idle speed was still too high (1.12). Again the vehicle was offered to the Suzuki dealer and a second repair round was executed. After repair of the leakages in the intake and exhaust system (new throttle valve body gasket, new spark plugs and a new exhaust muffler) the OBD codes were not active anymore and the measured lambda al low idle speed was 0.99.

The measured emissions in the on-road test with an average ambient temperature of 15 ºC were: CO_2 128.3 g/km, NO_x 187.0 mg/km and NH_3 63.3 mg/km.

Table 3-12: PTI test results of the Suzuki Wagon (Euro 3 @ 222,134 – 222,335 km)

	Low idle speed			**High idle speed**		
	CO	**NO_x**	**Lambda**	**CO**	**NO_x**	**Lambda**
Vehicle condition	**[vol%]**	**[ppm]**	**[-]**	**[vol%]**	**[ppm]**	**[-]**
As received	0.15	12	1.09	0.02	25	1.01
EGR valve repaired	0.18	1	1.17	0.09	7	1.01
Repair intake manifold and exhaust, new spark plugs.	0.21	0	0.99	0.01	10	1.00

Table 3-13: On road test results of the Suzuki Wagon (Euro 3 @ 222,134 – 222,335 km)

Vehicle condition	**Distance**	**Av. speed**	**CO_2**	**NO_x**	**NH_3**
	[km]	**[km/h]**	**[g/km]**	**[mg/km]**	**[mg/km]**
As received	48.0	44.4	140.7	296.2	32.8
EGR valve repaired	48.4	44.8	126.7	229.8	34.1
Repair leakage intake manifold and exhaust, new spark plugs.	48.0	46.3	128.3	187.0	63.3

Effect of repairs on the NO_x emission of the Suzuki Wagon:
The measured on-road NO_x emission of the Suzuki Wagon R+ 'as received' was 58% higher than the NO_x emission of the repaired vehicle (296.2 mg/km versus 187.0 mg/km). In both on road emission tests the NOx emissions was on a similar or lower level as the type approval limit value. In all executed PTI 4-gas tests the vehicle passed. If the OBD P-codes would be part of the pass/fail criteria of the PTI this vehicle would have failed.

3.6.2.3 *Peugeot 206 Euro 2 @ 251,836 km*

At first the Peugeot 206 with an odometer reading of 251,836 km was tested in the received condition. In addition the vehicle was repaired and the vehicle was retested. "According to the RDW database, the indicated mileage of 251,836 km was rated as 'not logic'. By using the odometer report the corrected mileage appeared to be 314,852 km.

Results intake, OBD diagnosis and PTI emission tests:
During the intake the vehicle seemed to run without major failures because the engine was running smoothly in a 35 km trip to the test location performed by TNO personnel.

The OBD system of this Euro 2 vehicle was not available/accessible. During the inspections at the intake of the vehicle no major failures were detected. Some small leaks in the exhaust system were repaired with gum.
In the PTI emission test the CO concentration at low idle speed was 0.00 vol% (@ lambda 1.03) and at high idle speed 0.78 vol% (@ lambda 1.02). The vehicle failed in this PTI test.

Three months earlier the vehicle passed the PTI in a regular Dutch PTI station. The person in charge of the PTI station was interviewed and explained that the vehicle passed the PTI emission test because the vehicle was preconditioned in a sportive road test followed by very high idle speed operation. Directly after this preconditioning the CO emission at high idle speed was shortly less than 0.30 vol% and as a result the vehicle passed the test.

Emission test results before and after repairs:
The unmodified vehicle was tested on the road and the measured emission, at an average ambient temperature of 19 ºC was: CO_2 134.8 g/km, NO_x 1267 mg/km and NH_3 37.0 mg/km. The PTI test was repeated and the CO concentration at low idle speed was 0.00 vol% (@ lambda 1.03). At high idle speed the measured lambda was 1.01 and the CO concentration was 0.80 vol%. With these PTI emissions the vehicle failed in the PTI.

A new three-way catalyst (replacement version) and exhaust system were installed by a local Peugeot dealer and the vehicle was preconditioned over a distance of 70 km and retested. After installation of the new three-way catalyst and exhaust system, the measured on road emission at an average ambient temperature of 21.0 ºC was: CO_2 139.6 g/km, NO_x 167.1 mg/km and NH_3 29.9 mg/km. In this on road test, at a speed of around 80 km/h, an unexpected high NO_x emission was measured. Furthermore, the lambda control seemed not very stable.
The PTI test was repeated and the CO concentration at low idle speed was 0.01 vol% (@ lambda 1.01). At high idle speed the measured lambda was 1.00 and the CO concentration was 0.01 vol%. With these PTI emissions the vehicle passed the PTI criteria.

In addition to the first repair round, a new lambda sensor was installed and the vehicle was tested again.
The measured on road emission with an average ambient temperature of 17 ºC was: CO_2 138.6 g/km, NO_x 87.0 mg/km and NH_3 28.3 mg/km.
The PTI test was repeated and the CO concentration at low idle speed was 0.00 vol% (@ lambda 1.00). At high idle speed the measured lambda was 1.00 and the CO concentration was 0.00 vol%. With these PTI emissions the vehicle passed the PTI test.

Table 3-14: PTI test results of the Peugeot 206 (Euro 2 @ 314,852 – 315,849 km).

	Low idle speed			**High idle speed**		
	CO	**NO_x**	**Lambda**	**CO**	**NO_x**	**Lambda**
Vehicle condition	**[vol%]**	**[ppm]**	**[-]**	**[vol%]**	**[ppm]**	**[-]**
As received	0.00	101	1.029	0.78	275	1.016
New three-way catalyst	0.01	0	1.005	0.01	83	1.003
New lambda sensor	0.00	5	1.003	0.00	0	1.000

Table 3-15: On road test results of the Peugeot 206 (Euro 2 @ 314,852 – 315,849 km)

Vehicle condition	Distance	Av. speed	CO_2	NO_x	NH_3
	[km]	[km/h]	[g/km]	[mg/km]	[mg/km]
As received	48.0	45.1	134.8	1266.5	37.0
New three-way catalyst	48.7	42.8	139.6	167.1	29.9
New lambda sensor	48.1	45.4	138.6	87.0	28.3

Analysis Peugeot 206:
The measured on-road NO_x emission of the Peugeot 206 ‘as received’ was 14.6 times higher than the NO_x emission of the repaired vehicle with new three-way catalyst and new lambda sensor (1266.5 mg/km versus 87.0 mg/km).
In the initial PTI high idle speed test the CO emission exceeded the limit value of 0.3 vol% and consequently the vehicle failed in the PTI.
Installation of a new three-way catalyst resulted in a NO_x reduction of 1099 mg/km (-87%) and in a second repair round the installation of a new lambda sensor resulted in a further NO_x reduction of 80 mg/km (-6.3%). With the new catalyst the vehicle had a PTI pass and the new NO_x sensor improved the lambda control and NO_x emissions substantially.
The preconditioning as used during the regular PTI test heavily determined the actual operating temperatures and CO conversion rates of the three-way catalyst and the PTI emission test results.

Effect of repairs on the NO_x emission of the Peugeot 206:
In the received condition (with a worn catalyst) the average on road NO_x emission of the Peugeot 206 was 1267 mg/km and in the PTI emission test the vehicle failed because the measured CO concentration at high idle speed was 0.78 vol%.
Installation of a new three-way catalyst and lambda sensor resulted in an average on road NO_x emission of 87 mg/km (reduction of 93 %) and a PTI pass.

3.6.2.4 Toyota Aygo Euro 4 @ 206,334 km

At first the Toyota Aygo with 206,334 km was tested in the received condition.
In addition the vehicle was repaired and the vehicle was retested.

Results intake, OBD diagnosis and PTI emission tests:
During the intake the vehicle ran smoothly but the MIL was burning and OBD code P0420 (Catalyst system efficiency below threshold bank 1) was active.
In the first PTI emission test the CO concentration at low idle speed was 0.04 vol% (@ lambda 1.00) and at high idle speed 0.26 vol% (@ lambda 1.00). The vehicle passed this PTI test.

Emission test results before and after repairs:
The unmodified vehicle was tested on the road and the measured emission at an average ambient temperature of 19 ºC was: CO_2 120.8 g/km, NO_x 264.3 mg/km / and NH_3 9.5 mg/km.
The PTI test was repeated and the CO concentration at low idle speed was 0.14 vol% (@ lambda 1.00). At high idle speed the measured lambda was 1.00 and the CO concentration was 0.49 vol%. With these PTI emissions the vehicle had a PTI fail.

A new three-way catalyst (replacement version) was installed by a local Toyota dealer and the vehicle was preconditioned over a distance of 120 km and retested.

The vehicle ran without an active OBD code and the MIL was off. After installation of the new three-way catalyst the measured on road emission at an average ambient temperature of 22.0 ºC was: CO_2 118.6 g/km, NO_x 19.9 mg/km and NH_3 21.0 mg/km.

Table 3-16: PTI test results of the Toyota Aygo (Euro 4 @ 206,334 – 209,373 km).

	Low idle speed			**High idle speed**		
	CO	**NO_x**	**Lambda**	**CO**	**NO_x**	**Lambda**
Vehicle condition	**[vol%]**	**[ppm]**	**[-]**	**[vol%]**	**[ppm]**	**[-]**
As received 1	0.04	0	1.00	0.26	184	1.00
As received 2	0.14	0	1.00	0.49	381	1.02
New three-way catalyst 1	0.04	0	1.00	0.00	0	1.00
New three-way catalyst 2	0.03	0	1.00	0.00	0	1.00

Table 3-17: On road test results of the Toyota Aygo (Euro 4 @ 206,334 – 209,373km).

Vehicle condition	**Distance**	**Av. speed**	**CO_2**	**NO_x**	**NH_3**
	[km]	**[km/h]**	**[g/km]**	**[mg/km]**	**[mg/km]**
As received	48.2	45.0	120.8	264.3	9.5
New three-way catalyst	49.4	43.4	118.6	19.9	21.0

Analysis Toyota Aygo:
The measured on-road NO_x emission of the Toyota Aygo 'as received' was 13.3 times higher than the NO_x emission of the repaired vehicle with new three-way catalyst and new lambda sensor (264 mg/km versus 20 mg/km).
In the initial PTI high idle speed test the CO emission was lower and higher than the limit value of 0.3 vol% and consequently the vehicle failed in the PTI.
Installation of a new three-way catalyst resulted in a NO_x reduction of 244 mg/km (-92. With the new catalyst the vehicle had a PTI pass and the on-road NO_x emissions decreased from 264 to 20 mg/km.

Effect of repairs on the NO_x emission of the Toyota Aygo:
In the received condition (with a worn catalyst) the average on road NO_x emission of the Toyota Aygo was 264.3 mg/km and in one PTI emission test the vehicle failed because the measured CO concentration at high idle speed was 0.49 vol%.
Installation of a new three-way catalyst and lambda sensor resulted in an average on road NO_x emission of 20 mg/km (reduction of 92 %) and a PTI pass.

4 Analyses of test results

In this chapter the test results of the chassis dynamometer program of 2018 [TNO 2018] and the on-road test program of 2020 are combined and analysed.

4.1 NO$_x$ emissions

4.1.1 Average NO$_x$ emissions of the (38 + 12) tested vehicles

In Table 4-1 the average NO$_x$ emissions of the chassis dynamometer test program of 2018 and of the on road test program of 2020 and the total, urban, rural and motorway average results of both test programs are reported.

The average NO$_x$ emission of the 50 tested vehicles is 200 mg/km (CF= 1.74). The total average NO$_x$ emission of the chassis dynamometer program with two Euro 4 high emitting vehicles is 305 mg/km (CF = 3.44) and substantial higher than the total average NO$_x$ emission of 166 mg/km (CF = 1.21) of the on road test program with one Euro 2 high emitting vehicle.

When the NO$_x$ emission of the three high emitting vehicles is assumed at an average value (related to the Euro class) of 100 and 250 mg/km, the total average NO$_x$ emissions of the 2018 and 2020 test programs are 130 and 144 mg/km. This indicates that the average test results of the chassis dynamometer test program and the on-road test program are similar.

Table 4-1: Overview of average NO$_x$ emission (total, urban, rural and motorway) of the tested vehicles and the test results of the 2018 chassis dynamometer test program.

	Number		**Total**	**Total**	**Urban**	**Rural**	**Motorway**
	of		**cold**	**warm**	**Warm**	**warm**	**warm**
	vehicles		**[mg/km]**				
2018	12		299	305	383	177	379
2020	38		-	166	206	119	155
Total	50		-	200	248	133	209

In Table 4-2 an overview of the very low, low, medium and high NO$_x$ emitting vehicles per test program is reported. In total 31 out of 50 vehicles have a conformity factor below 1 and 9 vehicles have elevated emissions (CF = 1–2). Seven vehicles have medium emissions (CF is 2-5 and NO$_x$ < 500 mg/km) and 3 vehicles are high emitters with an average NO$_x$ emission of 1191 mg/km.

In Table 4-3 an overview of shares of the very low, low, medium and high NO$_x$ emitting vehicles per test program is reported. In the first test program of 2018 1 out of 6 vehicles (16.7 %) had a very high NO$_x$ emission and 50% were very low emitters. In the second test program od 2020 1 out of 38 vehicles (2.6%) had a very high NO$_x$ emission and 66% were very low emitters. The shares of vehicles with elevated and medium NO$_x$ emissions were in both test programs nearly similar.

Table 4-2: Overview of low, medium and high NO_x emitting vehicles.

Category	**CF range [-] and NO_x**	**Number of vehicles**		
		2018	**2020**	**Total**
Very low emitter	< 1.0	6	25	31
Elevated	1.0 - 2.0	2	7	9
Medium emitter	2.0 – 5.0 and NO_x < 500 mg/km	2	5	7
High emitter	> 5.0 or NO_x > 500 mg/km	2	1	3
Total		12	38	50

Table 4-3: Overview of relative shares of low, medium and high NOx emitting vehicles.

Category	**CF range [-] and NO_x**	**Share of vehicles [%]**		
		2018	**2020**	**Total**
Very low emitter	< 1.0	50	66	62
Elevated	1.0 - 2.0	16.7	18	18
Medium emitter	2.0 – 5.0 and NO_x < 500 mg/km	16.7	13	14
High emitter	> 5.0 or NO_x > 500 mg/km	16.7	3	6
Total		100	100	100

Figure 4-1 shows the emission limit values incl. deterioration (lines) and average test results per Euro class of 38 on road tested petrol vehicles with high mileages (open triangles) and the total set of 50 (38 + 12) vehicles (filled up triangles).
The average NO_x test results of the chassis dynamometer and on road test program are similar for Euro 3 and 5 vehicles but deviate for Euro 2 and 4 vehicles because 2 Euro 4 vehicles (1103 and 1203 mg/km) were high emitters in the chassis dynamometer test program and 1 Euro 2 vehicle (1,267 mg/km) in the on road test program.

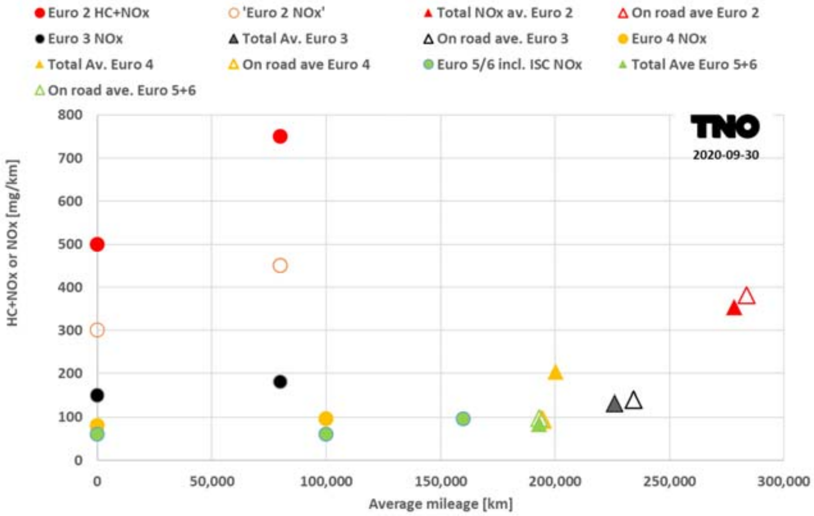

Figure 4-1: Emission limit values incl. deterioration and average test results per Euro class of 38 on road tested (open triangles) petrol vehicles with high mileages and the total set of 38 + 12 vehicles (filled triangles).

Analysis deterioration NO_x emission of older petrol vehicles.
On the basis of current Dutch NO_x emission factors (see section 1.1), the applied road test of 50.8 km (see section 2.4.2) and the division of the 50 tested vehicles over the Euro classes the average NO_x emission of the 50 tested vehicles in relative new condition (max. 50,000 km) would be 95 mg/km. In this test program the average measured NO_x emission of the 50 tested vehicles is 200 mg/km and this is 2.1 times higher than vehicles with a low mileage.

Analysis relative cumulative NO_x shares related to the total NO_x emission.
In Figure 4-2 the cumulative NO_x share of the 50 tested vehicles as function of the vehicle share is reported. The NO_x contribution of the three high emitting vehicles (6.0 % of the tested fleet) to the total average NO_x emission of the 50 tested vehicles is 35.8 %.

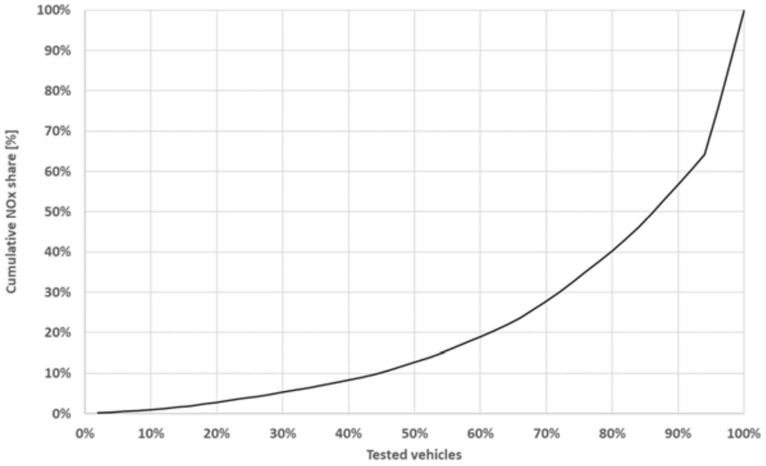

Figure 4-2: Cumulative NO_x share as function of the share of 50 tested vehicles.

4.1.2 Detailed NO_x emissions

- In Figure 4-3 the average on road NO_x emissions of all tested vehicles are reported, one could recognise two groups of vehicles: most vehicles have NO_x emissions below 400 mg/km. The NO_x emission of the three high emitters is in the range of 1,103 to 1,267 mg/km.
- In Figure 4-4 the relationship of vehicle age and the NO_x conformity factors are reported. The figure shows that there is no correlation between NO_x emission and vehicle age.
- In Figure 4-5 and Table 4-4, Table 4-5 and Table 4-6 the NO_x emissions of the tested vehicles per emission class are reported. The figure shows that there is no correlation between NO_x emission and emission class.
- In Figure 4-6 the NO_x conformity factors per Euro class are reported. There is no correlation between the NO_x conformity factor and Euro class.

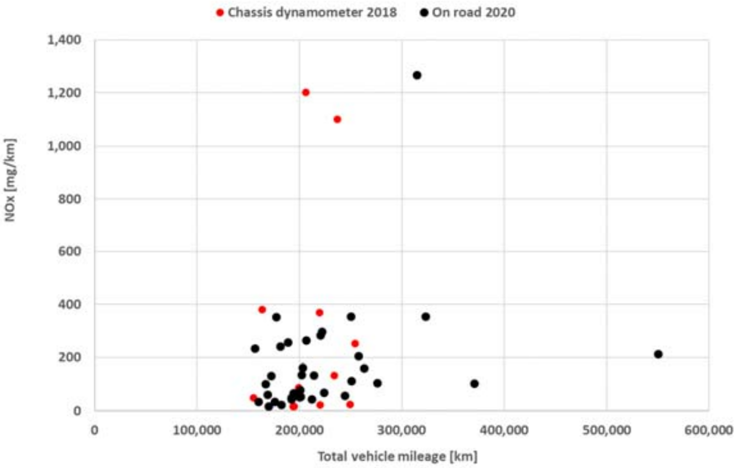

Figure 4-3: Average NO_x emissions of the 38 + 12 tested petrol vehicles with high mileages.

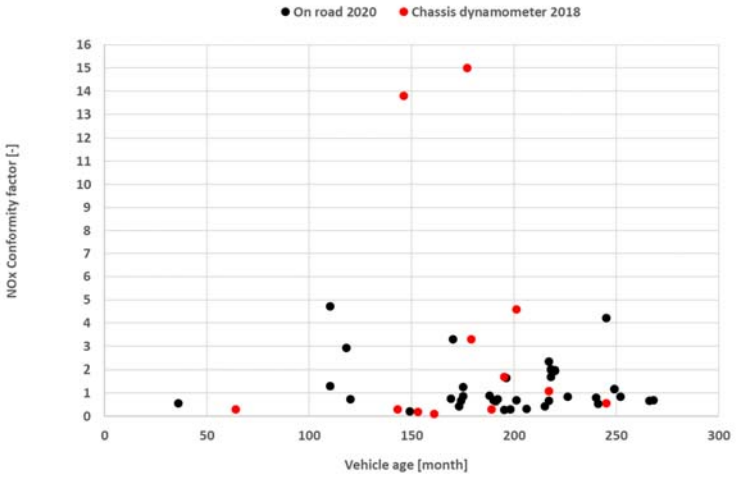

Figure 4-4: NO_x conformity factors of 38 + 12 petrol vehicles with high mileages related to vehicle age.

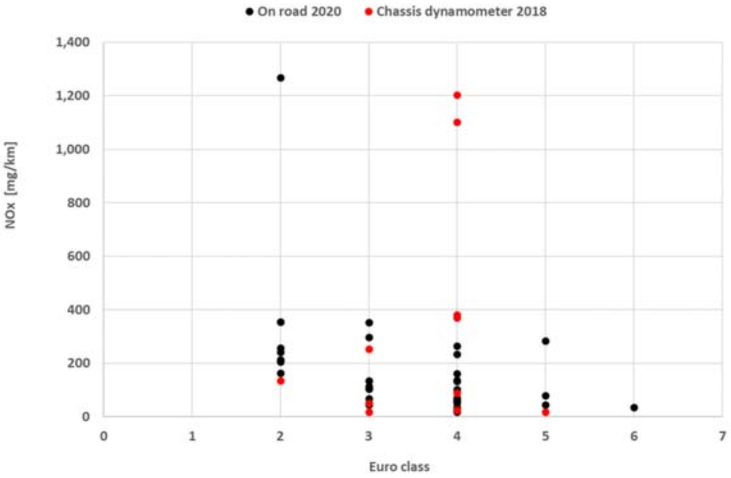

Figure 4-5: Average measured on road NO_x emission per Euro class of 38 + 12 petrol vehicles with high mileages.

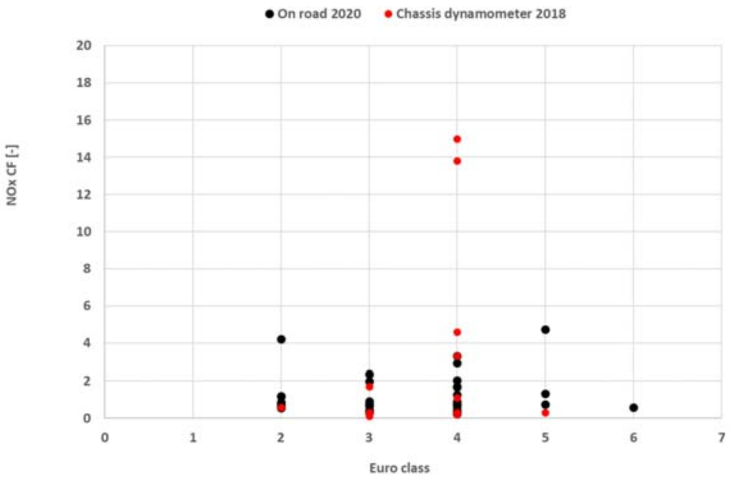

Figure 4-6: NO_x conformity factors of 38 +12 petrol vehicles per Euro class with high mileages.

Table 4-4: Average on road NO_x emission per emission class of 38 tested vehicles

	Euro 1	**Euro 2**	**Euro 3**	**Euro 4**	**Euro 5**	**Euro 6**
No. of vehicles	-	8	9	16	4	1
Av. NOx [mg/km]	-	382	140	95	113	35

Table 4-5: Average chassis dynamometer NO_x emission per emission class of 12 tested vehicles

	Euro 1	**Euro 2**	**Euro 3**	**Euro 4**	**Euro 5**	**Euro 6**
No. of vehicles	-	1	3	7	1	-
Av. NOx [mg/km]	-	134	107	456	17	-

Table 4-6: Average NO_x emission in mg/km per emission class of all 50 tested vehicles

	Euro 1	**Euro 2**	**Euro 3**	**Euro 4**	**Euro 5**	**Euro 6**
No. of vehicles	-	9	12	23	5	1
Av. NOx [mg/km]	-	354	132	205	94	35

On the three high NO_x emitting vehicles:
The Euro 2 Peugeot 206 had an average on road NO_x emission of 1267 mg/km. As reported in paragraph 3.7.2 after two repair rounds, the NO_x emission decreased further to 87 mg/km.

Both high emitting vehicles of the former TNO project (Fiat Punto and BMW 325 with NO_x emission of 1103 and 1203 mg/km) mainly operated with a deviating lambda control with an average lambda of 1.02. Under these conditions the CO was very well oxidised in the PTI tests and the vehicles passed the PTI. However the three-way catalyst didn't reduce NO_x with lean mixtures (lambda > 1). For a proper NO_x reduction in a three-way catalyst the average lambda must be around 0.99.

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4.2 Periodic Technical inspections

All 38 vehicles were tested according the Dutch PTI emission test procedure. Thirty one vehicles passed the PTI because they had no active OBD emission codes. The residual seven vehicles had active emission related OBD code and six of these vehicles passed the PTI emission test.
One vehicle (the Euro 2 Peugeot 206) did not pass the PTI CO emission criteria at high idle speed (CO concentration was 0.78 vol%). On the road the measured NO_x emission of this vehicle was 1267 mg/km.

When the PTI test results of the 12 vehicles of the chassis dynamometer test program are added, one out of 50 vehicles had a PTI fail. The two high emitting vehicles of the chassis dynamometer test program were not determined as a PTI fail.

Are medium and high NO_x emitters detected in the periodic technical inspection?
In this test program and the former test program [TNO 2018] the three high emitting vehicles had a NO_x emission in the range of 1103 to 1267 mg/km. Two were Euro 4 vehicles and they passed the PTI OBD and emission tests, the Euro 2 vehicle failed because the CO concentration at high idle speed was more than 0.39 vol%.
The two Euro 4 vehicles had no active OBD failures. So the OBD systems of the Euro 4 vehicles were not able to detect high NO_x emissions.
The failing Euro 2 vehicle with high a NO_x emission was not equipped with OBD and was detected as a vehicle with three-way catalyst with low CO oxidation performance.

Furthermore, the NO_x volumetric concentrations are not measured in the current PTI emission test and consequently the NO_x reduction performance of the three-way catalyst cannot be judged.

From all OBD systems the OBD system of the Toyota Aygo only reported a decreased efficiency of the three-way catalyst. As a prime example this OBD failure corresponded with the on-road NO_x emission of 264 mg/km (CF = 3.3). The OBD system of the Toyota Aygo was able to detect a decreased catalyst efficiency.

The OBD system of the BMW 320i mentioned a sulphured Lean NO_x catalyst (NO_x was 284 mg/km and CF = 4.7) but met the CO criteria of the PTI emission test. Normally the Lean NO_x catalyst is automatically regenerated by the emission control system of the vehicle when the right conditions (mostly at higher vehicle speeds) are present. The OBD system of the BMW 320i only indicated a certain status of the Lean NO_x catalyst.

Suzuki Wagon
The OBD system of the Suzuki Wagon mentioned a defective EGR system and lambda sensor. After repair of the EGR system it resulted in a decrease of the on-road NO_x emission.

4.3 Vehicle repairs

The NO_x emission of three out of four repaired vehicles reduced very strong (37, 92 and 93%).

However, the indication for the repair was based on the on-road measured NO_x emission with simultaneous active OBD code (Suzuki Wagon and Toyota Aygo) or a failing 4-gas PTI emission test (Peugeot 206).

The repair of the Fiat Punto (new lambda sensors) had no significant effect on the NO_x emission. This is typically an example of a vehicle with an increased NO_x emission without having failures of the OBD system or too high CO emissions in the PTI emission test.

4.4 Emissions with cold and warm engine starts

Four vehicles were tested in road trips (49 km) with cold and warm starts. In order to investigate the possible cold start effects the mass emissions of the first 7.2 km of these trips were calculated. In Table 4-7 the CO_2, NO_x and NH_3 mass emissions of the first 7.2 km of road tests with cold and warm start are reported.

For the Volvo and VW Polo the CO_2 emission of the first 7.2 km with a cold start are higher than with a warm start and for the Mazda and Citroen it was the other way around. Only the Mazda 5 had a higher NO_x emission with cold start than with a warm start. Apparently, fixed single road trips that are executed by different drivers with different ambient conditions resulted in a large spread in emission levels.
All tests with cold start had higher NH_3 emission than with a warm start.
In order to have a more clear view on on-road emission tests with cold and warm start a more dedicated test program with a higher number of tests is needed.

Table 4-7: Mass emissions of the first 7.2 km of a road trip

	Cold start			**Warm start**		
	CO_2	**NO_x**	**NH_3**	**CO_2**	**NO_x**	**NH_3**
	[g]	**[mg]**	**[mg]**	**[g]**	**[mg]**	**[mg]**
Volvo S60	2011	1200	656	1677	1355	488
VW Polo	1493	449	390	1135	673	340
Mazda 5	1732	868	471	1768	668	39
Citroen C2	1466	297	204	1513	609	75

4.5 Performance PTI emission test

4.5.1 Properties and analysis of the current PTI emission tests

The European Directive 2014/45/EC and the Dutch vehicle regulation (Wegenverkeerswet, Regeling Voertuigen) for periodic technical inspections (PTI) describe for positive ignited engines an emission test at low and high idle speed.
In this test the CO, THC, CO_2 and O_2 volumetric concentrations are measured and lambda is calculated on the basis of these measured concentrations.
The applicable CO limit values are meant to check the oxidation performance of the catalyst. There is no HC limit value, so the HC oxidation performance of the catalyst is not checked. Furthermore the NO_x concentration is not measured because it is not prescribed. Consequently the NO_x reduction performance of the three-way catalyst cannot be checked.
By means of a lambda measurement at high idle speed the functionality of the lambda control is checked. At high idle speed lambda must be in the band of 0.97-1.03.

Analysis of the preconditioning of the engine and three-way catalyst in a current 4-gas test:
Execution of PTI tests are defined with warm engine and the criteria for a warm engine are:

- Test trip with active cooling fan.
- Lubricant > 80 °C.
- 3 minutes with a minimum engine speed of 3000 rpm.

These three criteria of a warm engine will result in different conditions of the engine and temperature of the three-way catalyst in the PTI emission test.
In Figure 4-7 an example of a low and high idle speed test is shown. The HC and NO_x concentrations vary in time because the temperature of the three-way catalyst is, by nature, not stable and the conversion rate of the three-way catalyst is, among others, temperature dependent.

In the current PTI test procedure the sequence of the low and high idle speed test, durations of preconditioning, stabilisation and measuring times are not specified. Consequently the PTI emission test is very undefined with a random character. Furthermore this may result in a forced execution of the PTI test (with relatively high catalyst temperatures) obtaining most favourite conditions of the engine and/or catalyst.

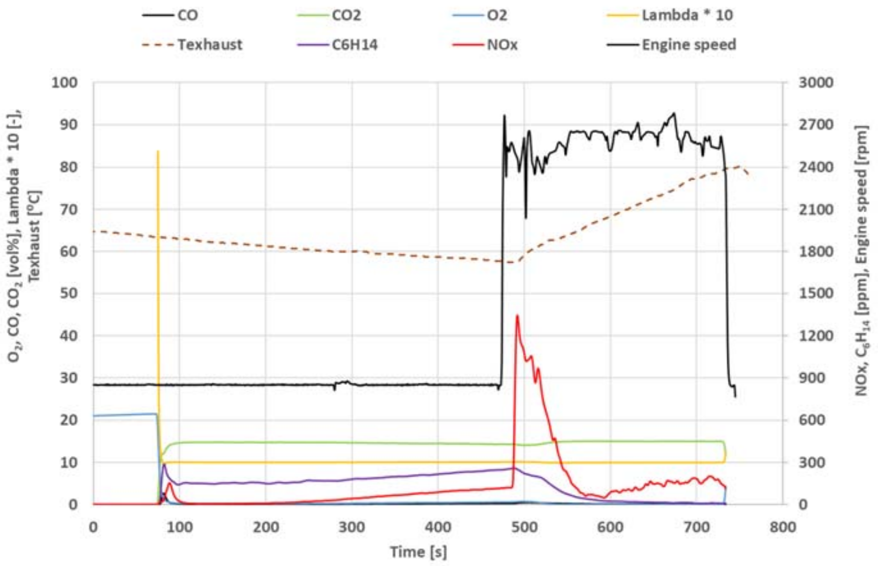

Figure 4-7: Low and high idle speed tests with warm engine of a Fiat Punto (Euro 4). Emission concentrations vary in time because the three-way catalyst cools down at low idle speed and warms up at high idle speed.

The nature of the criteria for a warm engine are defined as minimum cases. However the conversion rate of a catalyst increases with increasing temperatures and with current test criteria one is allowed to precondition the catalyst to a relatively high temperature (i.e. a test trip with high engine speeds or very high idle speeds).

In order to test with more realistic catalyst temperatures the preconditioning criteria of the PTI test must be extended with:

- A maximum vehicle speed (i.e. 80 km/h) with maximum engine speeds of 3200 rpm.
- A maximum engine speed for warming up at high idle speed (i.e. 3200 rpm)

Analysis of the measuring time of a 4-gas test.
Due to a lack of a defined measuring time in the European Directive and national PTI regulation the 4-gas test is practically a momentary check (or spot check). Consequently the vehicle passes/fails on the basis of a momentary result.

Analysis of the test sequence of a 4-gas test.
The European Directive and national regulation doesn't prescribe a test sequence and consequently the low and high idle speed tests can be randomly executed with a random preconditioning of both tests. In case of a prescribed sequence (i.e. 1. preconditioning, 2, low idle speed test and 3. high idle speed test) PTI tests can be executed with more defined and realistic test conditions.

Analysis of the CO limit values of a 4-gas test
From the measured CO concentrations at low and high idle speed (see Figure 3-7 and Figure 3-8) only one vehicle did not meet the CO emission PTI limit value of 0.30 vol% at high idle speed. This Peugeot 206 had an average on road NO_x emission of 1267 mg/km. In this specific case of the Peugeot 206 the CO oxidation and NO_x reduction performances of the three-way catalyst were near zero. On the contrary the two high emitting vehicles (BMW and Fiat) of the former research program [TNO 2018] passed the PTI (with sufficient CO oxidation performance but had a similar NO_x emission as the Peugeot 206. These results indicate that the CO reduction performance of a three-way catalyst is not related to the NO_x emission reduction performance.

Analysis of the lambda limit values of a 4-gas test:
The current allowed lambda window in the high idle PTI test is 0.97 to 1.03. This allowed lambda window is wider than the window of actual lambda values of the tested vehicles in this test program. For all well operating three-way catalysts the lambda values at high idle speed were in the range of 0.990 – 1.005. For the Peugeot 206 and Toyota Aygo with worn and deteriorated three-way catalyst the lambda values at high idle speed were 1.016 and 1.025.
If the PTI lambda limit value band will be tightened to 0.98 to 1.00 it is expected that more vehicles with elevated emissions will not pass the PTI.

4.5.2 *NO_x concentrations in low and high idle speed tests*

In this test program the NO_x concentration at low and high idle speed of all tested vehicles was measured. In Figure 4-8 the on-road NO_x emission of the 38 road trips as function of the measured NO_x concentration at low idle speed is plotted and in Figure 4-9 as function of the measured NO_x concentration at high idle speed. Both NO_x concentrations have a very poor correlation with the on-road NO_x emission.

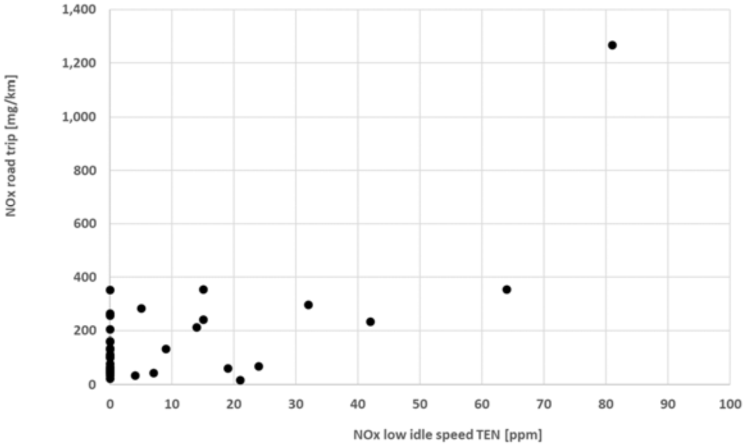

Figure 4-8: On-road NO_x emission of 38 tested vehicles as function of the NO_x concentration at low idle speed.

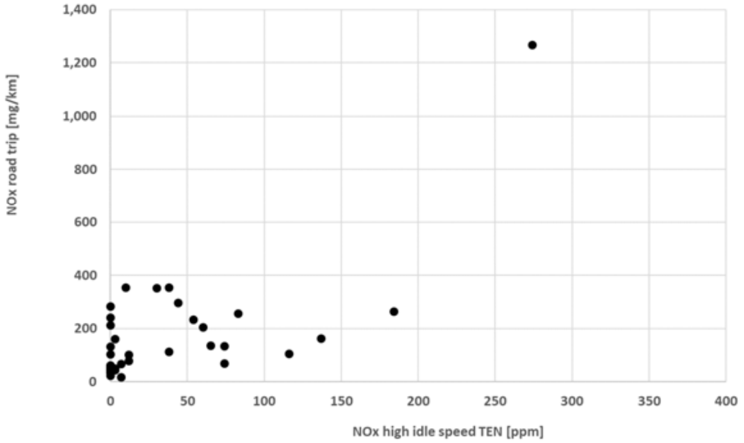

Figure 4-9: On-road NO_x emission of 38 tested vehicles as function of the NO_x concentration at high idle speed.

4.6 Quality of the measured NO_x concentrations

The quality of the NO_x concentrations measured with MEMS is validated from comparisons to chassis dynamometer measurements of a Euro 6 Volkswagen Polo petrol vehicle. This vehicle has an odometer reading of 175,000 km and EN 228 trade fuel (E10 grade) was applied. Two CADC tests with cold start tests and two CADC tests with warm start tests were performed, of which the details are described in Appendix A and B.

In Figure 4-10 the cumulative NO_x concentrations of these tests are shown.

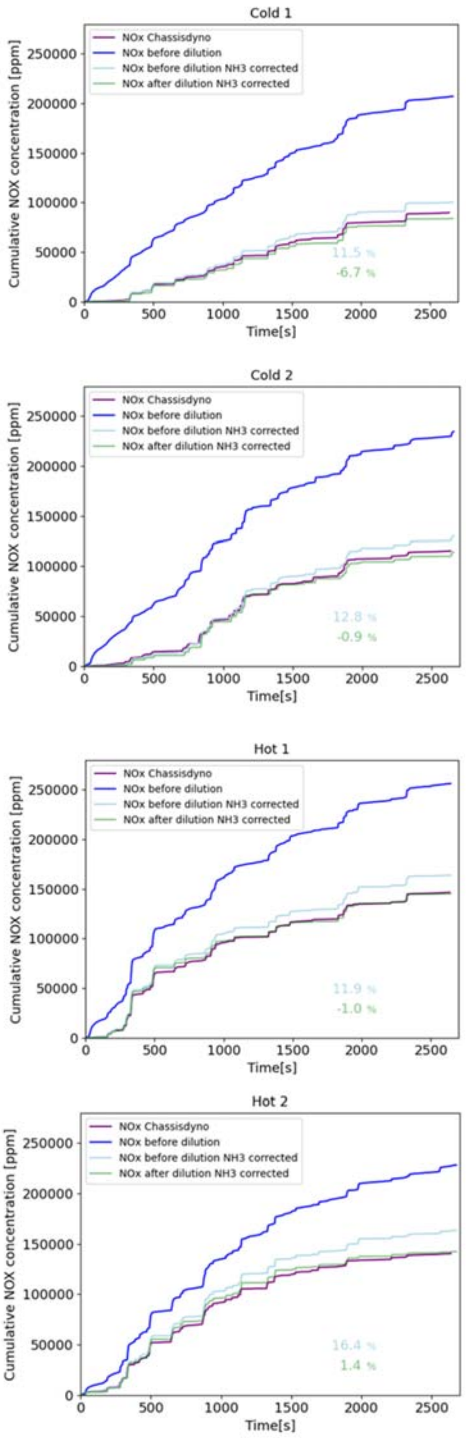

Figure 4-10: Cumulative NO_x concentrations of the two cold start (top panels) and two warm start (bottom panels) chassis dynamometer tests. The purple line indicates the chassis dynamometer results. The NO_x concentration MEMS measurements are performed in undiluted and diluted gas. The dilution factor is derived from the O_2 concentration of the undiluted and diluted gas. NO_x concentrations of undiluted gas is shown in dark blue. This signal is corrected for NH_3 interference by the diluted NH_3 MEMS measurement (light blue), which was first converted to undiluted NH_3 concentrations. NO_x concentrations converted from the diluted gas and corrected for NH_3 interference are shown in green. The percentages show the deviation from the chassis dynamometer NO_x concentration.

The NH_3- and dilution-corrected NO_x concentrations measured in diluted gas deviate between -6.7% to 1.4% from the measured NO_x concentrations in a chemiluminescent NO_x analyser. Undiluted and NH_3-corrected NO_x concentrations deviate between 11.5% and 16.4% from these reference NO_x concentrations.
The MEMS NO_x sensor is strongly influenced by NH_3 concentrations.
NH_3 corrections are therefore necessary to correctly derive the NO_x concentrations.
Since the MEMS NH_3 sensor is expected to perform poorly in oxygen depleted gas, NH_3 needs to be measured from the diluted gas.

4.7 NH_3 emissions

In this section the NH_3 emission of the tested vehicles is analysed in more detail.
At first average test results of all tested vehicles are presented and in addition detailed results per vehicle are investigated.

4.7.1 Average NH_3 emissions

In Table 4-8 an overview of the average NH_3 emissions (total and per road type) of the 38 on road tested vehicles is reported (NH_3 measurements were not executed in the chassis dynamometer test program). The total average NH_3 emission of the 38 on-road tested vehicles is 32.1 mg/km. On average the urban NH_3 emission per kilometre is 49.0 mg/km and more than two times higher than the NH_3 emission on rural roads and on the motorway.

Table 4-8: Overview of average NH_3 emission (total, urban, rural and motorway) of the 38 on road tested vehicles.

	Number		**Total**	**Total**	**Urban**	**Rural**	**Motorway**
	of		**cold**	**warm**	**warm**	**warm**	**warm**
	Vehicles		**[mg/km]**	**[mg/km]**	**[mg/km]**	**[mg/km]**	**[mg/km]**
2020	38		-	32.1	49.0	22.2	20.6

The NH_3 emissions of the 38 tested vehicle can be categorized as follows:

- Low emitters (< 10 mg/km), 6 vehicles
- Medium emitters (10-30 mg/km), 16 vehicles
- High emitters (> 30 mg/km), 16 vehicles

As shown in Figure 4-11 the NH_3 emissions of the tested vehicles have no correlation with vehicle age and Figure 4-12 indicates that NH_3 emissions also have no correlation with emission class.

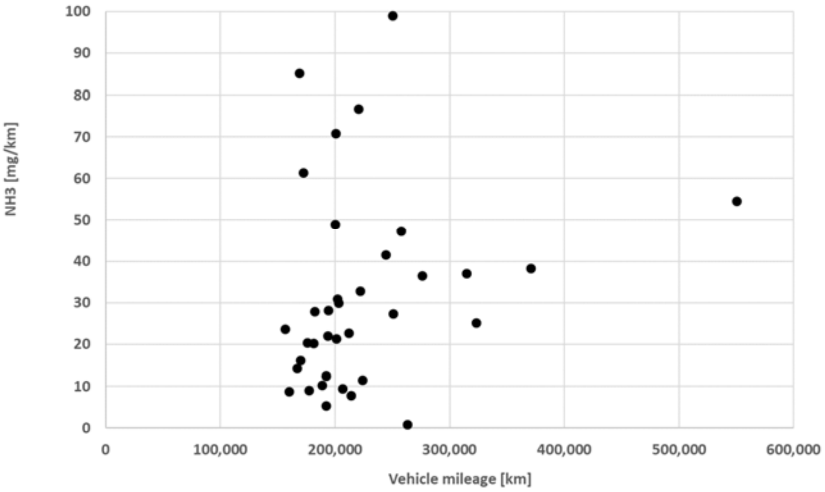

Figure 4-11: Average measured on road NH_3 emission as function of mileage of petrol vehicles.

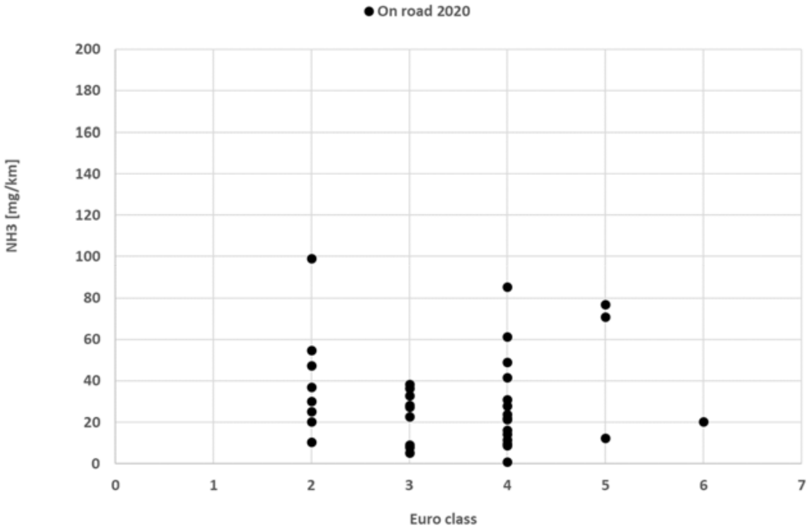

Figure 4-12: Average measured on road NH_3 emission as function of Euro class of petrol vehicles.

In Figure 4-13 the NH_3 mass emissions as function of their NO_x emission of 38 petrol vehicles are plotted; There is no correlation between the NO_x and NH_3 emissions.

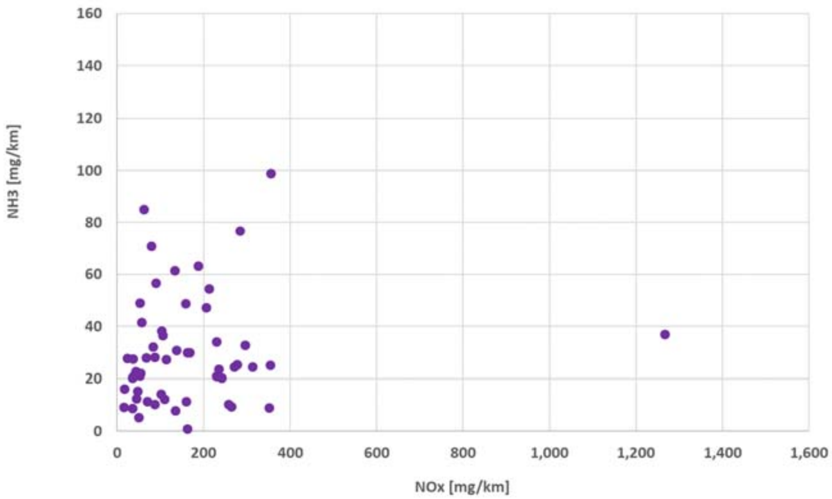

Figure 4-13: Average measured on road NH_3 emissions as function of average NO_x emissions of petrol vehicles.

NH_3 analysis of single vehicles
In order to understand the root cause of the NH_3 emission some measuring data of two vehicles were analysed in detail.

The on road test of the Toyota Avensis offers some clarity about the conditions of the NH_3 emission production. This vehicle operates with three air-fuel strategies. From 0 to 60 km/h the engine operates with stoichiometric air-fuel mixtures (lambda = 1.00) and above 60 km/h the engine operates with a lean mixture (lambda = 1.35). After cold start and during vehicle accelerations the air-fuel mixtures are rich (lambda < 1). In Figure 4-1 the cumulative NH_3 emission shows that the NH_3 emission is the very high at rich mixtures (lambda < 1), moderate at lambda = 1 and the lowest at lean mixtures.

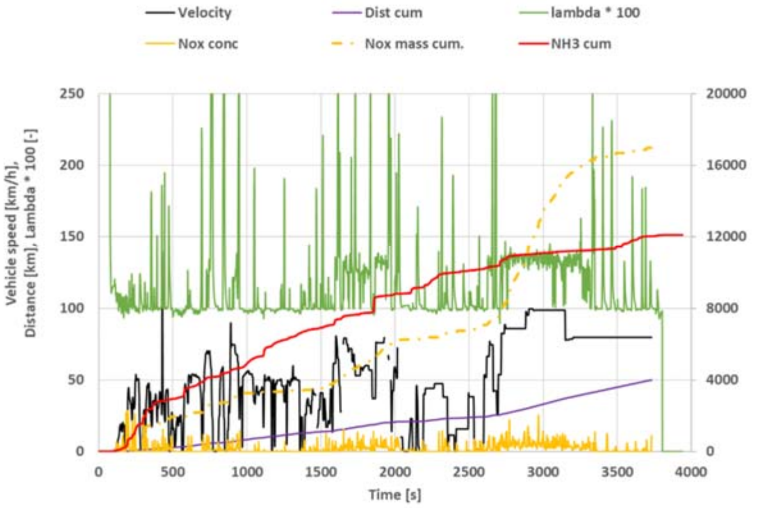

Figure 4-14: On road emission test of a Toyota Avensis.

In Figure 4-15 during the idle speed test of the VW Golf the air-fuel strategy changes (for unknown reasons) from stoichiometric to rich air-fuel mixtures (lambda decreases from 1.00 to 0.92). At the same time the NH_3 concentration increases from 70 to 200 ppm.

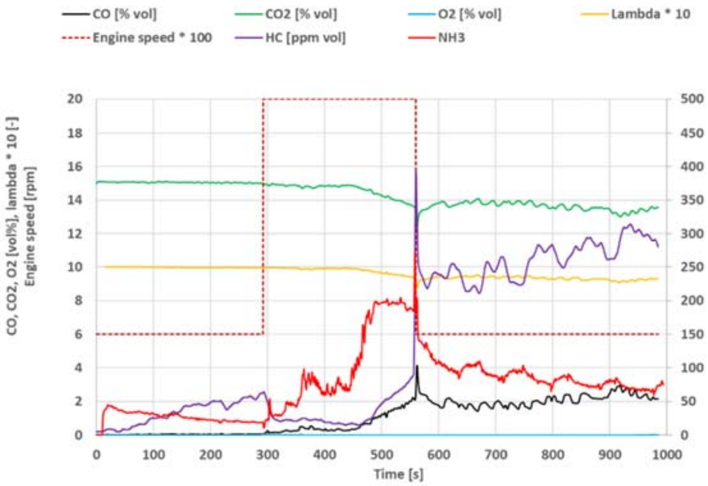

Figure 4-15: Idle speed tests of the VW Golf.

The test results of the Toyota Avensis and VW Golf show the relationship of lambda and NH_3 emissions. NH_3 emissions of petrol vehicles with a three-way catalyst are mainly produced with rich air-fuel mixtures

5 Discussion

5.1 Emissions

NO_x emissions and high emitters:
For 31 out of 50 tested vehicles the measured NO_x emission is (CF < 1), 9 vehicles have an elevated NO_x emission (CF = 1-2), 7 vehicles have medium NO_x emissions and 3 vehicles are high emitters with an average NO_x emission of 1191 mg/km. The contribution to the total NO_x emission of the three ‘high emitters’ out of 50 tested vehicles is 36%.
From repair actions it is clear there is a potential for improvement of the emissions of a vehicle with high NO_x emission. However the current in-field detection possibilities in service and inspection programs are very poor.

Durability of vehicle emissions:
Legal durability criteria of exhaust emissions of light duty road vehicles are set with mileage or time. Currently Euro 6 vehicles must comply 5 years or 100,000 km and this is checked in In Service Conformity test programs. Extra durability requirements are set for exhaust aftertreatment systems with deterioration factors up to a mileage of 160,000 km.

In the Netherlands vehicles run on average approximately 18 years before demolition and many vehicles run 250.000 km or more. From this perspective the current durability criteria don’t cover the whole vehicle life cycle. Furthermore, there is an insufficient systematics for determination of high emissions of defective vehicles and consequently effective enforcement is not possible. A vehicle owner may decide to skip repairs as long as the currently very poor PTI emission criteria are met.

New technologies and new possibilities for emission monitoring;
Due to the presence of NO_x emission sensors in new and future vehicles in combination with an appropriate OBD system the vehicle life time emissions can be monitored and guaranteed. Permanent information of vehicle emissions will probably build the awareness of vehicle owners, drivers and maintenance technicians. Due to the complexity of these monitoring systems vehicle manufacturers are the appropriate stakeholder for creating the right conditions for emission monitoring. The quality of such monitoring and OBD systems need to be checked by independent testing.

NH_3 emissions:
In this test program first attempts were made for measuring NH_3 emissions with a sensor in diluted exhaust gas. Measurements seemed reproducible in repetitive on-road tests.
The NH_3 emission of petrol vehicles with a three-way catalyst is related to air-fuel ratios of exhaust gas. Due to fuel abundancy at rich mixtures (lambda < 1) NH_3 is formed. With lean mixtures (lambda > 1) the NH_3 emission is relatively low.

Practically the lambda control of an engine is mainly optimised reaching the lowest CO, THC and NO_x emissions with a certain three-way catalyst configuration.
This optimisation is done with the lambda controller.

A certain lambda variation is programmed. The unregulated NH_3 emission is not taken into account and consequently it is not measured.

The configuration and calibration of the fuel control system determines the quality of the lambda control (variations, average lambda values, minimum and maximum values as well as the frequency of control). In most conditions the average lambda is set around 0.990 to 0.995 because the optimum three-way catalyst performance can be reached. However, lambda pre catalyst oscillates continuously and partly the engine runs with richer air-fuel mixtures (i.e. lambda oscillates between 0.985 and 0.995). The amplitude and frequency of the lambda control determines the NH_3 emission.

The spread of NH_3 emission is large because the average NH_3 emission of all on-road tested vehicles is 1 to 99 mg/km. For some vehicles (VW Golf, Nissan Primera, Peugeot 308, Seat Cordoba, BMW 320i, Kia Rio) it seems that the average lambda is set at richer mixtures because this results in maximum NO_x conversion in the three-way catalyst; The average NH_3 emission of these vehicle is relatively high (> 60 mg/km).
When NH_3 emission limit values are added to current emission legislation vehicle manufacturers have to optimize the trade of NO_x and NH_3 emissions applying a proper lambda control and possibly an extra oxidation catalyst.

Consequences in case of regulated NH_3 emissions:
When NH_3 emissions are regulated the NH_3 measuring technique must be defined by legislators. Secondly, the NH_3 limit values need to be developed and set.
In case of regulated NH_3 emissions for petrol vehicles with three-way catalyst a vehicle manufacturer must cope with the CO-NH_3 / NO_x trade of. This seems to be feasible because many tested vehicles already have low NO_x and NH_3 emissions (< 30 mg/km).

5.2 Investigations for an improved PTI emission test procedure

In current PTI tests vehicles with high NO_x emissions are not detected. The 4-gas test has only CO and lambda criteria, lambda criteria at high idle speed are too weak. Other weak points are the preconditioning of the vehicle and the very undefined test procedure.

On Board Diagnosis:
Current OBD systems are useful and very helpful for vehicle repairs but are not suitable for PTI purposes. This research proves that current OBD systems have insufficient performance for detection of vehicles with a high NO_x emission.
The OBD systems of the two Euro 4 vehicles with a very high NO_x emission had no active OBD codes. Furthermore, not all PTI stations have the state of the art OBD readers and consequently they cannot read the OBD information. Finally OBD systems can be manipulated.

In this emission test program different kinds of emission and PTI tests are executed, investigated and assessed. With these test results and insights the current test procedure might be improved to have a simple and low cost PTI emission test that correlates with real world emissions of vehicles.

One of the main findings of this research study is that the current PTI emission test doesn't detect vehicles with high NO_x emissions. For potential next steps of the improvement of the PTI test procedure the next options are pre-assessed:

Improved OBD:
Current OBD systems of petrol vehicles are mostly not able to detect high emissions. The BMW 325 and Fiat Punto (both Euro 4 vehicles with OBD system) of the former test program are good examples of vehicles with OBD-systems without active emission codes and very high NO_x emissions. Most tested vehicles with moderate NO_x emissions (CF = 2-4) also ran without active OBD codes.
If next generations of vehicles are equipped with suitable NO_x sensors a permanent emission monitoring is possible and even a continuous average emission can be shown to the driver.

Warming up emission test is useful but not practical:
In this test program the three-way catalyst performance was assessed in idle tests with a cold start, followed by a warming up and an idle test with warm engine. During warming up the catalyst efficiency increases. The emission reduction rate and the test time can be used to assess the catalyst performance. Sometimes the three-way catalyst needs very long warming up times and/or running at high idle speedto reach high conversions.

The main disadvantages of such a warming up test are the start with a cold engine (not practical in PTI context) and the required test time of 10 – 20 minutes. Furthermore the determination of the reduction rates is not easy because the emission concentrations with cold start are not stable.

NO_x emission test at idle speed seems not feasible:
In this test program the NO_x concentrations at low and high idle speed were measured. The NO_x test results in section 4.5.2 show a poor correlation between the NO_x concentrations at idle speeds and the on-road NO_x emission. Consequently measuring NO_x concentrations at idle speed is not option for a PTI emission test.

Potential for an improved PTI test procedure:
In section 4.2 the current PTI emission test procedure is investigated. Several weak points are determined and investigated. Potential improvements which should be further investigated and validated are: Revised criteria for preconditioning of the engine/catalyst, a revised test procedure (fixed sequence and duration of low and high idle speed test) and revised lambda limit values.

Some first ideas for a potential revised PTI emission test are given below:

Criteria for preconditioning:
In order to establish a realistic catalyst temperature the current three criteria for preconditioning must be modified:

- Test trip with active cooling fan and a maximum vehicle speed of 80 km/h and a maximum engine speed of 3200 rpm.
- Lubricant > 70 °C after 120 seconds low idle speed.
- Coolant temperature > 70 °C and < 3 minutes high idle speed of maximum 3200 rpm.

Test sequence:
A proposed mandatory test sequence is (see Figure 5-1):

1. Low idle speed
2. High idle speed.

Step and cycle times:
The minimum step times for low and high idle speed are 70 seconds (60 seconds stabilisation time and 10 seconds measuring time). The minimum test cycle time is 160 seconds. In Table 5-1 and Figure 5-1 the total test procedure with a minimum duration of 160 seconds is described.

Table 5-1: Option for a revised PTI emission test for petrol vehicles (engine is constantly running).

Activity	**Minimum time period [s]**	**Comment**
Warm up engine	t.b.d.	Representative catalyst temperature
Set low idle speed	0	
Install probe in tail pipe	0	
Stabilisation time	0 - 60	
Measuring time	60 – 70	Average of 10 samples
Set high idle speed	70 – 80	Auxiliaries activated
Stabilisation time	80 – 140	
Measuring time	140 – 150	Average of 10 samples
End of test	160	

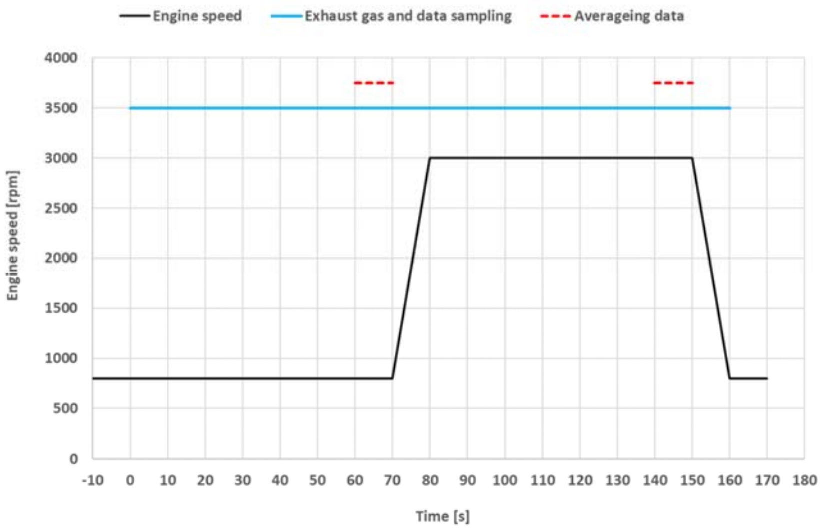

Figure 5-1: Option for a revised PTI test cycle.

Pass-Fail criteria:
The current CO criteria can stay unmodified.
The proposed revised lambda window at high idle speed is 0.98 to 1.00 and with a two digit reading this effective lambda window is 0.975 to 1.005 because this lambda window corresponds with the lambda window of the three-way catalyst, see Figure 5-2.

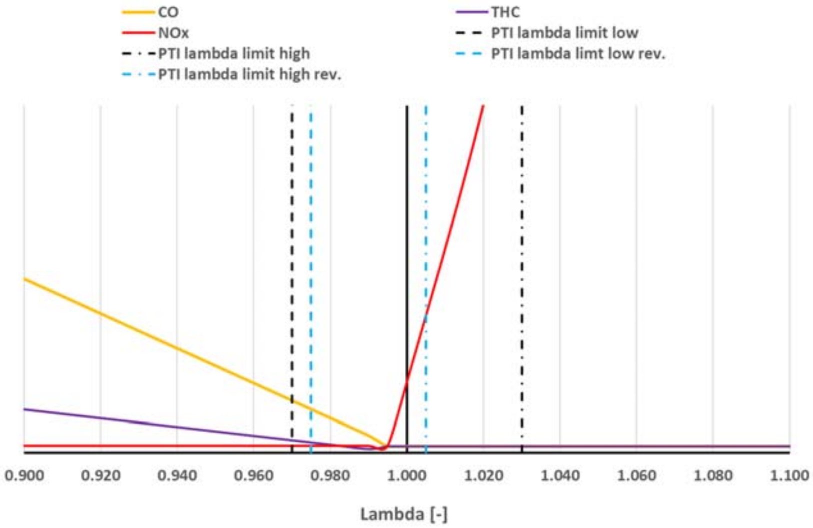

Figure 5-2: The typical emissions of a petrol engine and (revised) PTI lambda limit values. Within the current PTI lambda band when lambda is 1.01 to 1.03 the NO_x emissions are very high. In rich operation (lambda < 0.97) on the left hydrocarbon and CO emissions are high. Around lambda 0.995 HC, CO, and NO_x are produced in the right balance to be converted in a three-way catalyst into harmless products. The revised PTI lambda limit values (blue dotted vertical lines) correspond better with the lambda window of the three-way catalyst.

6 Conclusions

With the introduction of the three-way catalyst in 1992, petrol cars have become much cleaner than the older petrol- and diesel cars. Euro-3 petrol vehicles, which have to satisfy a more stringent test, reduce the NO_x emissions by a factor 20, compared to vehicles without a three-way catalyst. In the meantime many vehicles with high mileages run on European roads and there is a lack of emission data of these vehicles.

In this study, with real-world emission tests on the road and PTI emission tests at idle speeds, 38 vehicles with high mileages were tested. The results of an earlier similar TNO study of 12 vehicles, that was based on a chassis dynamometer test program, were integrated. The sorted conclusions are:

NO_x emissions:
The average warm NO_x emission of the 50 tested vehicles with an average mileage of 222,444 km is 200 mg/km and 74% higher than their type approval limit values, this can be marked as a very substantial deterioration.

The NO_x contribution of three (6%) high emitting vehicles to the total NO_x emission is 35.8%. If the technical failures of these vehicles would be detected and repaired the total average estimated NO_x emission of the 50 tested vehicles drops to 130 mg/km. This shows that detection of high NO_x emitters and subsequently repair of these vehicles has a strong positive effect on the average NO_x emission of this group of vehicles.

The analysed NO_x emission data of all 50 tested vehicles clearly show that the NO_x emissions of petrol vehicles with high mileages are not related to vehicle mileage (> 160,000 km), vehicle age, emission class, vehicle trade mark, type or model.

When the NO_x emission of the three high emitting vehicles is assumed at an average value (related to the Euro class) of 100 and 250 mg/km, the total average NO_x emissions of the 2018 and 2020 test programs are 130 and 144 mg/km. This indicates that the average test results of the chassis dynamometer test program and the on-road test program are similar.

Vehicles with a high mileage emit on average substantial more NO_x than new vehicles. The average measured NO_x emission of the 50 tested vehicles with an average mileage of 222,444 km is 200 mg/km and is on average 2.1 times higher than from these type of vehicles in new condition.

Current durability requirements don’t correspond with the average life-time mileage of the tested vehicles:
Per Euro class the average mileage of the tested vehicles is 1.2 to 3.5 times higher than the applicable durability mileage (i.e. 80,000 or 160,000 km). Consequently there is no reference for judgement of the emission performance of vehicles with a high mileage.

NH_3 emissions:
In this on-road test program the average measured NH_3 emission of 38 vehicles is 32 mg/km. Per vehicle it varies from 1 to 99 mg/km and this variation seem to be dependent on the air-fuel control strategies of the engines. The NH_3 emissions are not related to vehicle mileage (> 160.000 km), vehicle age or Euro class.
With cold engine conditions the NH_3 emission is relatively high. In the first 7.2 km of road tests with a cold start the measured NH_3 emission is 15 to 1208 % higher than in tests with a warm start.

Emissions with different driving styles:
The sportive driving style resulted in an increase of CO_2, NO_x and NH_3 emissions, these are: CO_2 13%, NO_x 96% and NH_3 39%.

Emission tests with cold and warm start:
Single on-road emission tests with cold and warm start of four tested vehicles showed inconsistent CO_2 and NO_x results. Multiple emission tests are needed for a solid assessment.

In idle speed tests with a cold start followed by a warming up of approximately 20 minutes at low idle speed the CO, THC and NO_x reduction rates (based on the measured concentrations) of the majority of the tested vehicles is above 80%.
For some vehicles this reduction rate was 50 – 80%. Only one vehicle had a very low emission reduction rate of 0-20%.
This warming up test may not be suitable for the PTI because the required test time is too long and the requirements for the start condition of the test are very strict. This warming up test might be a screening option for (In Service Conformity) emission test programs.

OBD systems:
OBD systems are not able to detect vehicles with a medium or high NO_x emission. The OBD systems of two Euro 4 vehicles with a high NOx emission which were tested on the chassis dynamometer had no active OBD codes. Furthermore active emission related OBD codes of the tested vehicles were not correlated with NO_x emissions and most vehicles with medium NO_x emissions (CF = 2 – 4) had no active OBD codes. Other vehicles with active OBD codes had a regular NO_x emission (CF < 2).

Periodic Technical Inspections:
The current PTI 4-gas test procedure is poor defined because mandatory instructions for the stabilisation and measuring times and the sequence of the low and high idle speed tests are not prescribed.

The current PTI CO emission test checks the CO oxidation performance of the three-way catalyst and the CO limit values seem to be not very stringent. Only one vehicle exceeded the CO limit value with normal preconditioning. The PTI CO test results are not correlated with the PTI NO_x concentrations.

The current PTI emission test has a very poor detection performance for high emitting vehicles, 37 out of 38 tested vehicles passed the PTI emission test. Only one vehicle with a high on-road NO_x emission of 1,267 mg/km didn’t pass.

However, this vehicle passed the regular PTI test with an excessive preconditioning which was executed a few months earlier. Six tested vehicles with a medium NO_x emission (CF = 2-4) also passed the PTI emission test. Furthermore, the two vehicles with a high NO_x emission of the chassis dynamometer test program of 2018 passed the PTI emission test as well.

NO_x measurements in the PTI:
For petrol vehicles with a three-way catalyst NO_x concentrations in idle tests have a very poor correlation with the on-road NO_x emission. Therefore an extension of the current PTI emission test procedure with a NO_x measurement at idle speeds is not suitable. Adding a NO_x measurement at idle speed would result in false positive and false negative PTI test results.

Vehicle repairs are effective:
Repairs of four tested vehicles with a high NO_x emission are effective.
From 3 out of 4 vehicles with a medium or high average on-road NO_x emission the vehicle repairs resulted in an average reduction of the on-road NO_x emission of 37 – 93%. From 2 vehicles the three-way catalyst was replaced and the EGR-system of the third vehicle was repaired. The repair of the fourth vehicle was not effective. Presumably this three-way catalyst has also a reduced conversion efficiency.

Potential improvements of the current PTI emission test procedure:
The current PTI emission test procedure for petrol vehicles which is described in EC Regulation 2014/45 is not suitable for detection of high emitting vehicles. Especially vehicles with high NO_x emissions are not detected. An additional NO_x measurement at idle speeds is not a solution for the PTI but a better defined emission test procedure with revised lambda criteria seems feasible and more effective for detection of vehicles with a high NO_x emission.

Potential improvements are:

- Better criteria for preconditioning of the three-way catalyst:

Catalyst efficiencies mostly increase with increasing operating temperatures.
The current criteria for preconditioning of the vehicle in a PTI emission test are defined with minimum requirements, the catalyst should reach a certain operating temperature. Excessive preconditioning of the catalyst which result in a higher operating temperature is allowed In order to avoid unrealistic test conditions (too high catalyst temperature) the preconditioning of the vehicle must be defined with requirements that limit the temperature of the catalyst.

- Defined test cycle:

In order to improve the quality of the PTI emission test result, a minimum stabilisation time, measuring time, a measuring frequency and the standard deviation of the test result should be prescribed.

- Defined test procedure:

In order to improve the reproducibility and repeatability of the PTI emission test result a defined test sequence of the current low and high idle speeds should be prescribed.

- Improved lambda limit values:

The current lambda limit values (0.97 to 1.03) of the PTI emission test doesn't correspond with the lambda window of three-way catalysts. In order to avoid passing vehicles with high NO_x emissions it is advised to limit the range of lambda values to 0.98 to 1.00.

Emission tests with different driving styles:
Four vehicles were tested with a regular and sportive driving style. The sportive driving style resulted in an increase of CO_2, NO_x and NH_3 emissions, these are on average CO_2 13%, NO_x 96% and NH_3 39%.

Validation mobile emission measurement system:
On the basis of chassis dynamometer tests and the flow validation of the exhaust flow meter of the Mobile Emission Measurement System (MEMS) it is estimated that the average on road measured CO_2 emission of MEMS is 6 to 8% higher than the CO_2 emissions of the chassis dynamometer (CVS-bag). The average estimated NO_x emission of MEMS is 10 to 14 % lower than the measured NO_x emissions of the chassis dynamometer. From these validation results it is concluded that MEMS is suitable for screening of average CO_2 and NO_x emissions of petrol vehicles.

7 Recommendations

The European Directive 2014/45/EC and the Dutch vehicle regulation (Wegenverkeerswet, Regeling Voertuigen) for periodic technical inspections (PTI) describe a similar PTI emission test procedure for petrol vehicles. At low and high idle speed the tail pipe emission concentrations have to be measured.
Several weak points in this test procedure result in false positive test results, these are:

- The three described preconditioning options in combination with the description of the low and high idle speed tests may lead to unrealistic (too high) operating temperatures in the PTI emission tests.
- No described sequence and duration of low idle and high idle speed tests.
- No defined stabilisation time of the engine and three-way catalyst,
- The test result is a momentary value and not an average value over a certain measuring time.

In order to improve the current PTI emission test procedure for positive ignited engines with three-way catalyst the development of a more defined emission test procedure is recommended which defines maximum values of certain criteria.
It is expected that the revised PTI emission test procedure will result in a higher and more realistic PTI failure rate of defective vehicles with high a NO_x emission.

In order to get a better view on the share of vehicles of the total Dutch fleet with high emissions it is recommended to study statistical data from PTI data bases.

8 Abbreviations

AAT	Ambient Air Temperature
CADC	Common Artemis Driving Cycle
CF	Conformity Factor
CO	Carbon monoxide
CO_2	Carbon dioxide
ECT	Engine Coolant Temperature
EMF	Exhaust Mass Flow
EGR	Exhaust Gas Recirculation
EOBD	European On Board Diagnostics
GPS	Global Position Sensor
LFE	Liquid Fuel Economy
MAF	Mass Air Flow
MEMS	Mobile Emission Measurement System
MIL	Malfunction Indication Light
NEDC	New European Driving Cycle
NH_3	Ammonia
NO_x	Nitrogen Oxides ($NO + NO_2$)
O_2	Oxygen
OBD	On Board Diagnostics
PTI	Periodic Technical Inspection
RON	Research Octane Number
SEMS	Smart Emission Measurement System
THC	Total Hydro Carbons

9 Acknowledgements

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Further acknowledgements go to RDW (the Dutch type approval authority and responsible for periodic technical inspections in The Netherlands) for their input and discussion on PTI related subjects of this study.

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11 Signature

The Hague, 17 December 2020

TNO

Chantal Stroek
Research Manager STL

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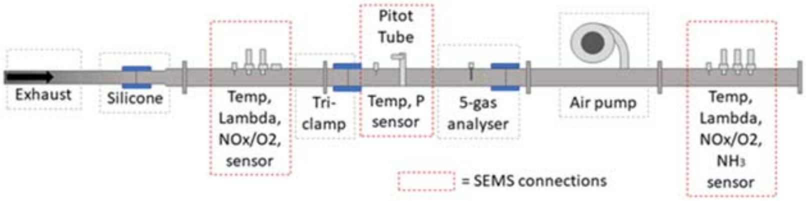
Author

A Specifications of the Mobile Emission Measurement System (MEMS)

MEMS contains the next modules:

1. A modified bicycle carrier.
2. Stainless steel tubing (internal diameter 38.3 mm @ length of 240 cm)
3. An automotive Exhaust Mass Flowmeter (EFM) (Horiba B-type, 0 – 4.5 m^3/min) which consists of a pitot tube, a pressure sensor box and a thermocouple.
4. An Automotive Exhaust Gas Tester (TEN Innova) with CO, CO_2, C_6H_8, O_2 and NO_x analysers and on-line lambda calculation. Measuring frequency is 4 Hz. This unit sampled undiluted exhaust gas and powered with a 12/230 V DC convertor.
5. A dilution air pump that has a fairly constant mass flow of 5 g/s.
6. 2 Continental NO_x – O_2 , 1 Delphi NH_3 and 2 lambda automotive sensors and 2 thermocouples. Undiluted and diluted gas was measured.
7. A GPS sensor.
8. A SEMS data logger that is connected to the OBD-system (if present) and sensors. Measuring frequency 10 Hz.
9. Electrical power (12V battery) for the MEMS.
10. Central database and postprocessing of emission mass flow rates.
11. Access to processed data via internet.

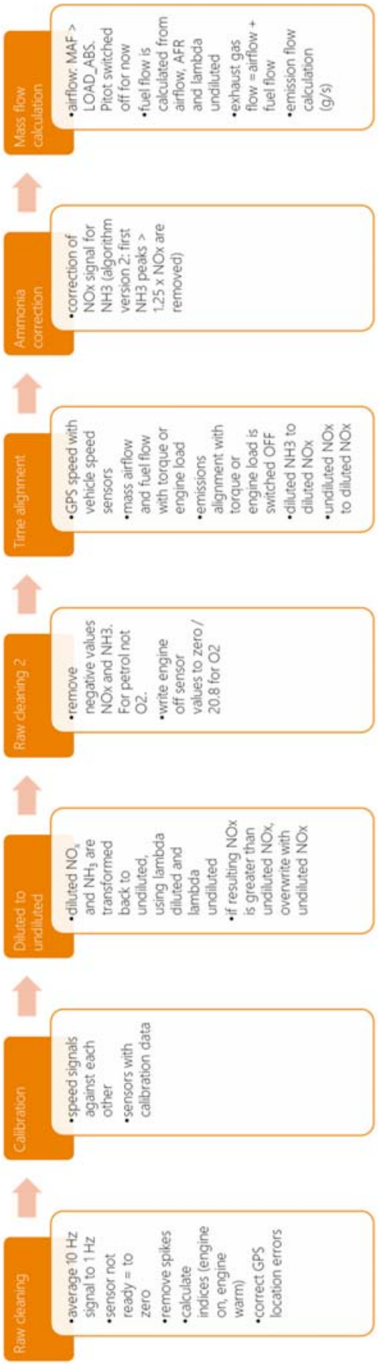
Schematic overview of the Mobile Emission Measurement System.



Specification sensors;

NO_x - O_2:	Continental.	SNS 155A , 5WK96755A
NH_3:	Delphi.	Part Number 5801627706
Lambda:	Bosch.	LSU 4.9

Data processing architecture:
Note: For diesel vehicles the sample rate of data acquisition is 1 Hz and exhaust gas dilution is NOT applied.



B Validation of the Mobile Emission Measurement System

B.1.1 Validation on the chassis dynamometer.

In section 2.3 and Appendix B the configuration of the Mobile Emission Measurement System is described. MEMS was validated using Common Artemis Driving Cycles on a chassis dynamometer because the configuration was new and the MEMS performance was unknown.

All emission tests were carried out on a Euro 6 VW Polo petrol vehicle with an odometer reading of 175,000 km, EN 228 trade fuel (E10 grade) was applied. In Table 11-1 the activities of the chassis dynamometer test program are specified and in Table 11-2 the applied road load settings. Soaking of the vehicle and emission testing were carried out with an ambient temperature of 23 ºC.

Figure 11-1: Validation of MEMS on the chassis dynamometer.

Table 11-1: Chassis dynamometer test program of the VW Polo Euro 6 petrol.

Day	Emission test
0	Soak
1	CADC cold start
1	CADC warm start
1/2	Soak
2	CADC cold start
2	CADC warm start

Table 11-2: Road load settings on the chassis dynamometer.

Parameter	Unit	Value
Inertia	**[kg]**	**1550**
F0	[N]	130
F1	[N/(km/h)]	0.00
F2	[N/(km$^{2/}$h$^{2)}$]	0.040

Mass Air Flow (MAF) and Liquid Fuel Economy (LFE) data were available on the OBD port and they were logged. The exhaust mass flow (EMF) was determined with a Horiba pitot flow meter. Due to initial technical imperfections of the pitot flow meter the validation was split into two parts:
Step 1: Chassis Dynamometer emission validation on the basis of MAF + LFE
Step 2: Exhaust flow validation on the road (EMF versus MAF + LFE).

Results chassis dynamometer emission validation:
In CADC tests with cold start the average CO_2 emission of the chassis dynamometer was 152.4 g/km and MEMS measured on average 156.0 g/km (difference is + 2.4%), see Figure 11-2. In CADC tests with warm start the average measured CO_2 emission of the chassis dynamometer was 151.7 g/km and MEMS measured on average 153.8 g/km (difference is +1.4%).
The average NO_x emission in the CADC tests with cold start of the chassis dynamometer was 55.6 mg/km and MEMS measured on average 45.7 mg/km (difference -18%), see Figure 11-3. In the CADC tests with warm start the NO_x emission of the chassis dynamometer was on average 66.2 mg/km and MEMS measured on average 56.6 mg/km (difference -15.5 %).

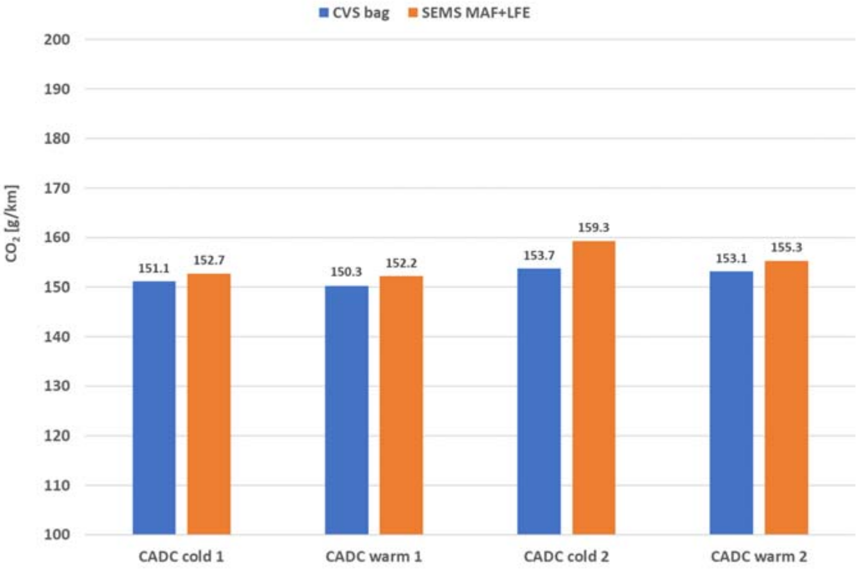


Figure 11-2: CO_2 CADC test results with cold and warm starts of the VW Polo Euro 6 petrol measured on the chassis dynamometer (CVS-bag) and with MEMS (MAF + LFE based).

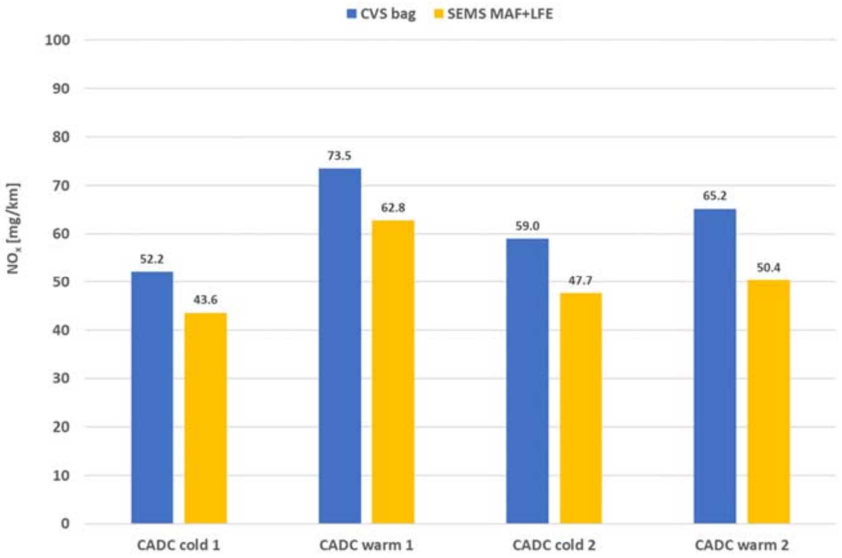


Figure 11-3: NO_x CADC test results with cold and warm starts of the VW Polo Euro 6 petrol measured on the chassis dynamometer (CVS-bag) and with MEMS (MAF + LFE based).

The measured NH_3 emissions (MAF + LFE based) in CADC tests with cold start are 10.9 and 10.0 mg/km and with hot start they are 9.7 and 8.2 mg/km, see Figure 11-4. These results are not validated.

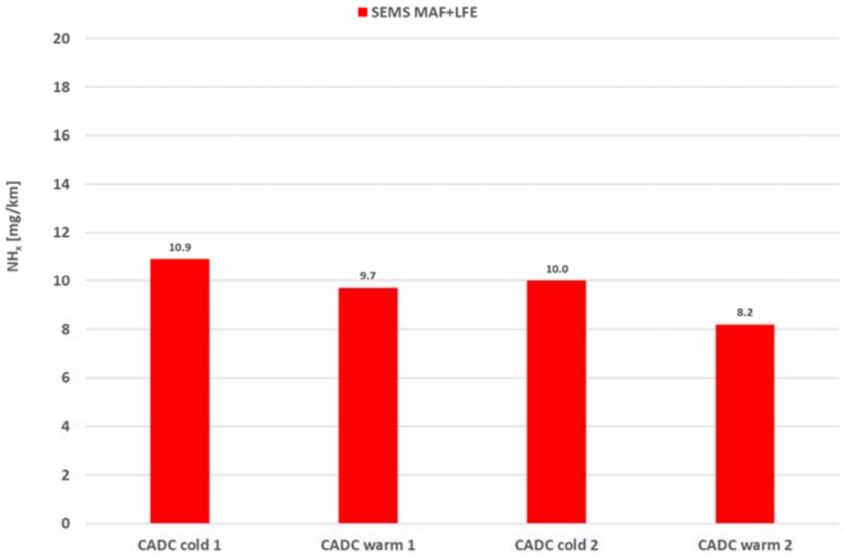


Figure 11-4: NH_3 CADC test results with cold and warm starts of the VW Polo Euro 6 petrol measured with MEMS (MAF + LFE based).

B.1.2 *Exhaust mass flow validation on the road.*

In a second step the flow characteristics of the pitot tube were validated with the MAF and LFE of the VW Polo in on road tests with a length of 48 km. In order to check the repeatability the test was repeated three times. The total measured exhaust masses of the pitot tube in the three executed on road tests were 3.8 to 6.4 % higher than the MAF + LFE based exhaust masses and the repeatability of this measurement is good, see Table 11-3. An example of cumulative exhaust masses of one on road test is given in Figure 11-5.

Table 11-3: Mass flow results of the pitot tube and vehicle sensors (MAF + LFE)

	Distance	**Duration**	**EMF pitot**	**MAF + LFE**	**Delta flow (EMF versus MAF+LFE)**
			cum.	**cum.**	
	[km]	**[s]**	**[g]**	**[g]**	**[%]**
Test 1	48.29	4130	29497	27717	6.4%
Test 2	48.26	3918	28566	27491	3.9%
Test 3	48.29	4419	29599	28526	3.8%

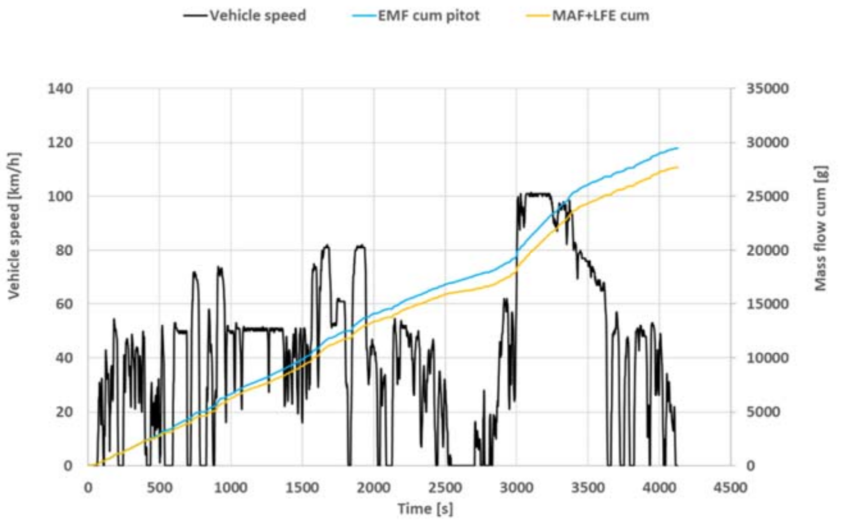


Figure 11-5: Cumulative exhaust mass flows of an on road test of 49 km of the VW Polo Euro 6 petrol measured with the pitot tube (EMF) and the vehicle sensors (MAF + LFE).

B.1.3 *On road repeatability check of the test procedure with MEMS.*

The repeatability of the on road test was checked with the Euro 6 VW Polo in three equal on road tests. The tests with a length of 48.3 km were started with a warm engine and executed on one day and the start-stop system was activated.

In Table 11-4 the test results of the three on road tests are reported. Average ambient temperatures in the three tests were 12.8, 15.9 and 16.4 ºC. Due to traffic conditions the duration of the three tests varied from 3918 to 4419 seconds. Exhaust mass flows were measured in two ways.

The cumulative pitot tube mass flows were on average 3.8 to 6.4% higher than the cumulative exhaust mass flows based on MAF and LFE readings from the vehicle. The average measured CO_2 emissions of the three tests were 111.4, 109.8 to 114.3 g/km, the NO_x emission was 34.7, 108.8 and 46.9 mg/km and the NH_3 emission was 20.4, 12.2 and 15.3 mg/km.

The deviating NO_x emission in the second test of 108.8 mg/km was caused by extremely high measured NO_x concentrations of the automotive NO_x sensor in the latest 600 seconds of the test. This NO_x sensor measures also O_2 concentrations and these measuring signals were also disturbed. As a fall back option the NO_x concentrations were always simultaneously measured with an automotive 5-gas analyser and these NO_x measurements didn't have deviating high numbers. In the third on road test and in the residual test program such NO_x deviations were not measured. For the time being the deviating NO_x results in the second test are stated as a single failure.

Table 11-4: Test results of three repetitive on road tests of the VW Polo with MEMS.

Test	**Dist.**	**Dur.**	**AAT**	**EMF pitot**	**MAF + LFE**	**Delta**	**CO_2**	**NO_x**	**NH_3**
				cum.	**cum.**	**Mass**			
	[km]	**[s]**	**[ºC]**	**[g]**	**[g]**	**[%]**	**[g/km]**	**[mg/km]**	**[mg/km]**
1	48.29	4130	12.8	29497	27717	6.4%	111.4	34.7	20.4
2	48.26	3918	15.9	28566	27491	3.9%	109.8	108.8	12.2
3	48.29	4419	16.4	29599	28526	3.8%	114.3	46.9	15.3

A detailed analysis of the measured NO_x concentrations of the applied NO_x-O_2 sensors is reported in section 4.6.

B.1.4 *Conclusions of the validation of MEMS:*

On the basis of chassis dynamometer tests and the flow validation of the exhaust flow meter of the Mobile Emission Measurement System (MEMS) it is estimated that the average on road measured CO_2 emission of MEMS is 6 to 8% higher than the CO_2 emission measured with the chassis dynamometer (CVS-bag).
The average estimated NO_x emission of MEMS is 10 to 14 % lower than the NO_x emissions measured with the chassis dynamometer.
On the basis of the validation results of MEMS it is concluded that MEMS is suitable for screening of average CO_2 and NO_x emissions of petrol vehicles.

C Tested vehicles

No	Brand	Model	Euro Class	Power [kW]	Year of first Registration	Odometer [km]	Empty Mass [kg]
1	VW	Polo	6	70	2017	175,728	1,011
2	Fiat	Punto	4	48	2010	156,604	1,005
3	Citroen	C5	3	100	2002	177,478	1,342
4	Toyota	Starlet	2	55	1998	257,829	905
5	Suzuki	Wagon R	3	56	2001	222,134	885
6	Opel	Corsa	4	43	2001	223,735	880
7	Suzuki	Swift	4	75	2005	166,851	975
8	Toyota	Yaris	4	64	2003	182,411	870
9	Toyota	Avensis	2	81	1999	323,151	1,315
10	Peugeot	406	2	81	2000	203,034	1,385
11	VW	Golf	2	150	1999	250,090	1,415
12	BMW	3	4	105	2002	262,826	1,295
13	Ford	Focus	2	74	2000	181,228	1,093
14	Peugeot	206	2	55	2000	251,836	925
15	Volvo	S60	3	147	2002	307,843	1,570
16	Renault	Clio	3	72	2003	192,048	975
17	Mazda	5	4	85	2006	159,708	1,370
18	Toyota	Aygo	4	50	2006	206,334	795
19	Nissan	Primera	4	85	2004	172,273	1,318
20	Citroen	C2	3	54	2004	213,774	966
21	VW	Passat	4	96	2003	243,970	1,376
22	VW	Passat	2	110	1998	550,384	1,295
23	Volvo	V40	3	90	2002	193,920	1,255
24	Mercedes	C180K	4	105	2006	193,458	1,435
25	Renault	Laguna	4	125	2008	200,949	1,463
26	Renault	Clio	2	55	1999	188,895	935
27	Citroen	Berlingo	3	80	2004	211,780	1226
28	Renault	Megane Sc	3	83	2004	276,102	1,420
29	Peugeot	206	3	44	2004	250,611	885
30	Opel	Zafira	4	77	2002	202,250	1,293
31	Peugeot	308 SW	5	88	2011	200,690	1,381
32	Seat	Cordoba	4	74	2006	168,964	1,041
33	Ford	Focus	4	85	2006	200,121	1,139
34	BMW	320i	5	125	2011	220,292	1,345
35	Skoda	Octavia	5	77	2010	192,181	1,205
36	Opel	Corsa	4	66	2008	169,682	1,063
37	Hyundai	Tucson	4	104	2010	199,577	1,437
38	Kia	Rio	5	63	2011	176,074	1,004

D On road emission test results

No	Trade mark - model	Euro Class	CO_2	NH_3	NO_x	
			[mg/km]	[mg/km]	[mg/km]	CF
1	VW Polo	6	111.4	20.4	34.7	0.3
2	Fiat Punto	4	151.3	23.7	237.1	3.0
3	Citroen C5	3	180,0	12.1	351.6	2.3
4	Toyota Starlet	2	160,5	45.2	196.7	0.7
5	Suzuki Wagon R+	3	140.7	32.8	296.2	2.0
6	Opel Corsa	4	124.0	11.5	69.0	0.9
7	Suzuki Swift	4	145.0	14.2	101.0	1.3
8	Toyota Yaris	4	132.5	27.9	23.8	0.3
9	Toyota Avensis	2	150.8	25.1	353.7	1.2
10	Peugeot 406	2	178.1	30.0	162.8	0.5
11	VW Golf	2	209.3	99.0	355.2	1.2
12	BMW 3	4	192.7	0.8	161.7	2.0
13	Ford Focus	2	143.1	20.3	241.9	0.8
14	Peugeot 206	2	134.8	37.0	1266.5	4.2
15	Volvo S60	3	180.4	38.3	103.2	0.7
16	Renault Clio	3	148.1	5.3	49.8	0.3
17	Mazda 5	4	176.5	8.7	35.5	0.4
18	Toyota Aygo	4	120.8	9.5	264.3	3.3
19	Nissan Primera	4	193.0	61.4	133.0	1.7
20	Citroen C2	3	155.3	7.9	134.0	0.9
21	VW Passat	4	212.6	41.6	56.8	0.7
22	VW Passat	2	192.9	54.6	212.5	0.7
23	Volvo V40	3	173.0	28.1	67.3	0.4
24	Mercedes C180K	4	183.2	22.0	54.2	0.7
25	Renault Laguna	4	216.6	21.3	52.9	0.7
26	Renault Clio	2	150.6	10.3	257.2	0.9
27	Citroen Berlingo	3	173.6	22.7	43.4	0.3
28	Renault Megane Sc	3	197.9	36.5	104.8	0.7
29	Peugeot 206	3	148.7	27.4	113.3	0.8
30	Opel Zafira	4	158.1	30.8	136.6	1.7
31	Peugeot 308 SW	5	154.9	70.9	79.5	1.3
32	Seat Cordoba	4	171.5	85.2	61.6	0.8
33	Ford Focus	4	182.5	49.0	52.1	0.7
34	BMW 320i	5	124.6	76.8	284.2	4.7
35	Skoda Octavia	5	160.3	12.4	44.3	0.7
36	Opel Corsa	4	158.3	16.1	17.4	0.2
37	Hyundai Tucson	4	205.2	13.8	62.1	0.8
38	Kia Rio	5	141.5	70.6	43.8	0.7

E Technical comments of the tested vehicles

No.	Make - model	Technical comments
1	VW Polo	-
2	Fiat Punto	-
3	Citroen C5	-
4	Toyota Starlet	No OBD available.
5	Suzuki Wagon R+	EGR system defective, intake air leakage. OBD codes: P0400 and P0130. CO emission @ low idle speed not stable.
6	Opel Corsa	-
7	Suzuki Swift	-
8	Toyota Yaris	CO emission @ low idle speed not stable.
9	Toyota Avensis	No OBD available. Lean burn engine > 60 km/h.
10	Peugeot 406	No OBD available.
11	VW Golf	OBD codes 17840 and 17538. CO emission @ low idle speed not stable.
12	BMW 3	-
13	Ford Focus	-
14	Peugeot 206	No OBD available. Three-way catalyst defective.
15	Volvo S60	-
16	Renault Clio	-
17	Mazda 5	-
18	Toyota Aygo	OBD code P0420. Three-way catalyst reduced performance.
19	Nissan Primera	-
20	Citroen C2	Low idle speed variation +/- 50 rpm.
21	VW Passat	Coolant high at low speeds. Cooling fan defective.
22	VW Passat	Actual three-way catalyst age is 190,000 km.
23	Volvo V40	Coolant 70 to 100 ºC (thermostat defective).
24	Mercedes C180K	Coolant 47 to 80 ºC (thermostat defective).
25	Renault Laguna	-
26	Renault Clio	CO emission @ low idle speed not stable.
27	Citroen Berlingo	-
28	Renault Megane Sc	-
29	Peugeot 206	-
30	Opel Zafira	-
31	Peugeot 308	CO emission @ low idle speed not stable.
32	Seat Cordoba	Static friction brakes.
33	Ford Focus	OBD code P000A: Position of camshaft slow reaction Coolant 57 to 77 ºC (thermostat defective).
34	BMW 320i	Shared lean burn and stoichiometric concept.
35	Skoda Octavia	-
36	Opel Corsa	-
37	Hyundai Tucson	OBD codes P011 and P016.
38	Kia Rio	New engine @ 105,000 km.

F PTI emission test results

Table 11-5: PTI test results of idle tests of tested petrol vehicles with warm engines (average of 15 seconds after stabilisation). The vehicles were tested ‘as received’.

				Low idle speed	**High idle speed**		
	Vehicle	**Euro Class**	**MIL On/Off**	**CO [vol%]**	**CO [vol%]**	**Lambda [-]**	**PTI Result Pass / Fail**
1	VW Polo	6	Off	0.00	0.00	1.000	Pass
2	Fiat Punto	4	Off	0.10	0.12	0.996	Pass
3	Citroen C5	3	Off	0.00	0.00	1.000	Pass
4	Toyota Starlet	2	Off	0.00	0.01	0.998	Pass
5	Suzuki Wagon**	3	Off	0.15	0.02	1.009	Pass
6	Opel Corsa	4	Off	0.02	0.02	1.000	Pass
7	Suzuki Swift	4	Off	0.02	0.00	1.000	Pass
8	Toyota Yaris**	4	Off	0.00	0.11	0.997	Pass
9	Toyota Avensis	2	Off	0.00	0.08	0.997	Pass
10	Peugeot 406	2	Off	0.14	0.00	1.012	Pass
11	VW Golf**	2	Off	0.28	0.30	0.991	Pass*
12	BMW 3	4	On	0.00	0.00	1.000	Pass
13	Ford Focus	2	Off	0.00	0.00	1.000	Pass
14	Peugeot 206	2	Off	0.00	0.78	1.015	Fail
15	Volvo S60	3	Off	0.02	0.02	0.999	Pass
16	Renault Clio	3	Off	0.01	0.01	1.000	Pass
17	Mazda 5	4	Off	0.03	0.08	0.998	Pass
18	Toyota Aygo	4	On	0.08	0.17	0.999	Pass*
19	Nissan Primera	4	Off	0.00	0.01	1.000	Pass
20	Citroen C2	3	Off	0.00	0.00	1.000	Pass
21	VW Passat	4	Off	0.00	0.00	1.000	Pass
22	VW Passat	2	Off	0.10	0.04	0.999	Pass
23	Volvo V40	3	Off	0.00	0.00	1.001	Pass
24	Mercedes C180K	4	Off	0.00	0.00	1.000	Pass
25	Renault Laguna	4	Off	0.00	0.00	1.000	Pass
26	Renault Clio**	2	Off	0.01	0.29	0.992	Pass
27	Citroen Berlingo	3	Off	0.02	0.00	1.001	Pass
28	Renault Megane Sc	3	Off	0.00	0.00	1.000	Pass
29	Peugeot 206	3	Off	0.12	0.00	1.000	Pass
30	Opel Zafira	4	Off	0.18	0.00	1.000	Pass
31	Peugeot 308**	5	Off	0.18	0.23	0.990	Pass
32	Seat Cordoba	4	Off	0.32	0.00	0.999	Pass
33	Ford Focus	4	Off	0.00	0.10	0.995	Pass
34	BMW 320i	5	Off	0.00	0.00	2.477	Pass
35	Skoda Octavia	5	Off	0.00	0.00	1.000	Pass
36	Opel Corsa	4	Off	0.01	0.00	0.999	Pass
37	Hyundai Tucson	4	Off	0.00	0.00	1.000	Pass
38	Kia Rio	5	Off	0.24	0.17	0.995	Pass

*After on road preconditioning, **Emissions are not stable.

G Backgrounds of NO_x emission control strategies

In order to understand the measured emission behaviour of all tested vehicles first some background knowledge of EGR-systems, three-way catalyst and the lambda control strategy is given.

EGR systems

Exhaust gas recirculation (EGR) systems are mainly applied to reduce NO_x and CO_2 emissions at low engine loads. The share of inert exhaust gas reduces the operating temperature of the combustion chamber which results in lower NO_x production. Furthermore EGR reduces pumping losses of the engine which results in a lower CO_2 emission.

Three-way catalysts

Three-way catalysts convert CO and HC to CO_2 and H_2O when the catalyst runs in its temperature window and sufficient O_2 is available for oxidation. These lean mixture conditions are available when the so-called lambda value exceeds 0.995. However NO_x is reduced in the warm catalyst when sufficient CO is available with rich mixtures at lambda values lower than 0.995. In the left part of Figure 11-6 the relationship of lambda and conversion of emissions in a three way catalyst is shown. Optimal conversion of CO THC and NO_x emissions can be realised in a very narrow lambda window which can be established with a so-called lambda controller which contains a lambda sensor.

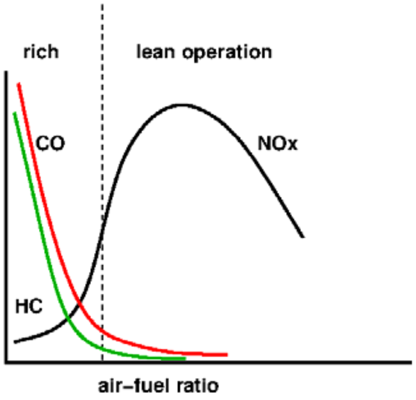


Figure 11-6: The typical emissions of a petrol engine. In lean operation, on the right, NO_x emissions are high. In rich operation on the left hydrocarbon and CO emissions are high. In between, at the dashed line, HC, CO, and NO_x are produced in the right balance to be converted in a three-way catalyst into harmless products.

Both conditions, rich and lean, are realised with the lambda controller which oscillates between a rich and lean mixture. The normal lambda operating window of lambda controlled engine with a three-way catalyst is in the range of 0.99 to 1.00. At higher engine loads mixture enrichment is applied, lambda can be around 0.80.

The determination of the mixture quality around a lambda value of 1.00 is measured by the lambda sensor which is basically an oxygen sensor. The output signal of the lambda sensor is 50 to 950 mV and a very steep switch of the sensor output signal occurs at lambda 1.00.

A small shift of this sensor measuring signal, which can be caused by deterioration, may lead to an effective average leaner mixture and a decreased conversion of the three way catalyst.

Requirements of lambda control
When lambda is below 0.99 CO is not oxidised and NO_x can be reduced. In vehicle applications lambda pre catalyst oscillates between i.e. 0.985 and 0.995 (see example in Figure 11-7). This very subtle lambda variation in the required lambda window with a frequency of appr. 1 Hz enables a three-way catalyst to oxidise CO and HC and to reduce NO_x. In case of a lambda deviation the performance of a three way catalyst is immediately changed.
In order to have a maximum conversion rate of the three-way catalyst the lambda must be set in the required lambda window. Very small deviations (when the air-fuel mixture is too lean, i.e. 1.00 instead of 0.99) can lead to substantial higher NO_x emissions, see Figure 11-6.

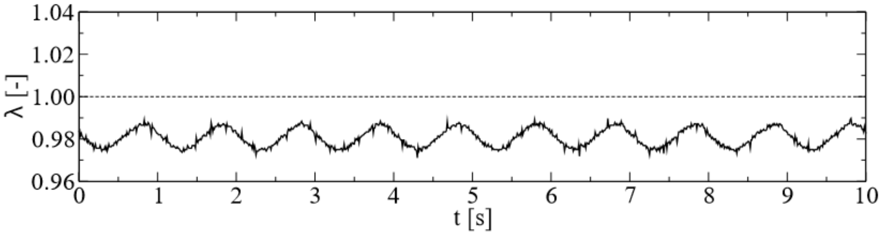


Figure 11-7: Exhaust air to fuel ratio upstream of the catalyst during rich bias conversion experiments (Δλ =±0.01, f =1 Hz) Reference [Brinkmeier 2006]

The four potential main causes for increased NOx emissions are:
- A failing EGR system
- A failing lambda sensor
- A failing air-fuel control system
- Catalyst deterioration

H Backgrounds of NH_3 emissions

The applied test set up contained an ammonia sensor to measure the ammonia emission of all vehicles under test. As an unregulated emission component for light duty vehicles, ammonia (NH_3) is not very often measured in emission tests. So first a short literature study of ammonia emissions of three-way catalysts was executed.

Adams et al. [Adams 2014] tested different types of catalysts in a steady state gas bench with various lambda values.

From the results, see Figure 11-8, the relationship of lambda and the formation of ammonia can be split in three sections:

- With lean mixtures (lambda > 1) the formation of ammonia is negligible.
- With rich mixtures (lambda < 1), the formation of ammonia is related to lambda.
- For some catalyst types the operating temperature and water-gas-shift have an effect on the ammonia formation but all catalysts produced ammonia with rich mixtures.

The formation of ammonia in three way catalysts seem to depend on the actual lambda value and is similar to the formation of CO (see Figure 11-6).

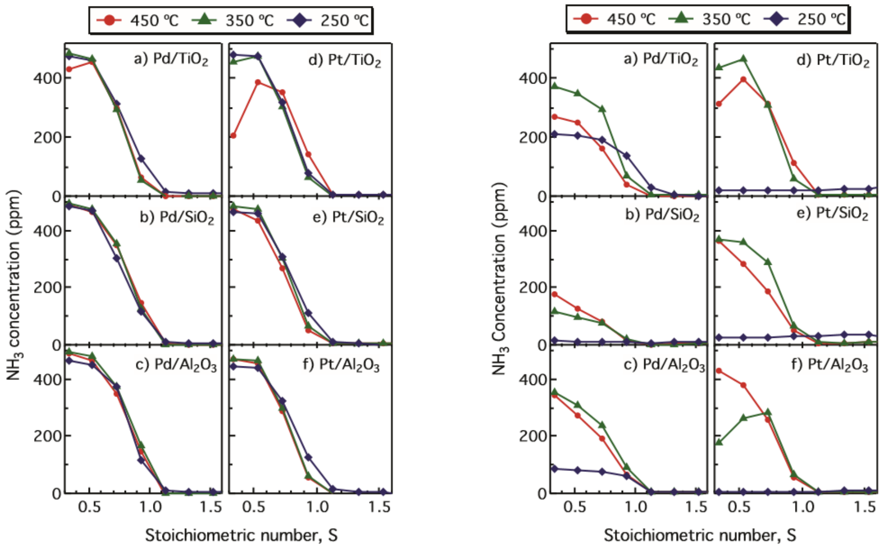


Figure 11-8: Steady-state formation of NH_3 versus oxygen concentration at 250, 350 and 450 ◦C (left figure non Water Gas Shift (WGS) assisted and right figure WGS assisted). The gas feed contained 500 ppm NO and 1500 ppm H_2 while the O_2 concentration was varied between 0 and 1050 ppm (S = 0.33–1.73) in steps of 150 ppm. Air was used as balance and space velocity was 40,000 h^{-1} [Adams 2014] .

A second study [Oh 2013] confirmed the formation of ammonia in different types of three-way catalysts with rich mixtures (lambda < 1).