NOx high emitters in the Dutch fleet

Characterizing the problem and researching methods for recognizing petrol high emitters

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Samenvatting

Eerdere onderzoeken[1,2] uitgevoerd door TNO in opdracht van het Ministerie van Infrastructuur en Waterstaat hebben laten zien dat de Nederlandse vloot benzinevoertuigen bevat die sterk verhoogde NO_x emissies hebben. Naar aanleiding hiervan is binnen de programmatische samenwerking tussen het Ministerie van Infrastructuur en Waterstaat en TNO op het gebied van voertuigemissies vervolgonderzoek uitgevoerd. Doel hiervan was om meer inzicht te verkrijgen in het aandeel van deze voertuigen in het wagenpark, de hoogte van de emissies van deze voertuigen op de weg en het verkennen van mogelijkheden tot betere detectie van voertuigen met een verhoogde NO_x emissie.
Dit onderzoek bestaat uit vier delen rond hetzelfde thema. De resultaten hiervan zijn samengevat in dit rapport.

NO_x emissies van de benzinevloot door middel van pluimmetingen
In voorgaand onderzoek zijn de emissies van voertuigen op individuele basis uitgebreid getest en hoewel dit een gedetailleerd inzicht geeft in het emissiegedrag van elk doorgemeten voertuig, bood dit onvoldoende statistische basis voor het bepalen van de impact van de gemeten voertuigen met verhoogde NO_x emissies op het totaal. TNO heeft derhalve een nieuwe methode ontwikkeld voor het uitvoeren van pluimmetingen op de weg en deze methode ingezet tijdens dit onderzoek. Pluimmeting is een vorm van ‘meten op afstand’. Voor metingen aan voertuigen op de openbare weg is een voertuig speciaal uitgerust met instrumenten om de emissies van vele voertuigen in korte tijd te kunnen meten, de snuffelbus.

De resultaten van 120 gemeten personenvoertuigen biedt een eerste inzicht in de NO_x emissies van de benzine- en dieselvoertuigen in de Nederlandse vloot. De eerste resultaten bevestigden de verwachting dat de NO_x emissies stijgen met kilometerstand, maar ook dat er een grote spreiding van de NO_x emissies is bij voertuigen met lage kilometerstanden. Dit is echter een tussenresultaat, de snuffelbus wordt in 2024 ingezet om meer voertuigen met deze speciale methode te meten.

NO_x emissies bij katalysatordiefstal en vervanging
In Nederland is de Toyota Prius, en zijn gelijkaardige voertuigen van het merk, het grootste slachtoffer van katalysatordiefstal. Voor het vervangen van de katalysator zijn er verschillende opties met variërende prijzen. Voor de eigenaar kan het aantrekkelijker zijn om voor een goedkopere niet-originele vervangingskatalysator te kiezen. De vraag is hoe deze vervangingskatalysatoren presteren ten aanzien van de NO_x emissie in de praktijk. Een meetprgramma is uitgevoerd om een eerste beeld te krijgen. Hiervoor is een tweede generatie Toyota Prius met zowel de originele katalysator als vijf niet-originele alternatieven onderworpen aan emissietesten op de weg.

Uit de resultaten kwam naar voren dat het vervangen van de katalysator kan leiden tot een toename in de NO_x emissies in de stad van 1200 mg/km, ofwel 34 maal de emissies met de originele katalysator.

[1] On road emissions of 38 petrol vehicles with high mileages, TNO report 2020 R11883
[2] Emissions of twelve petrol vehicles with high mileages, TNO report 2018 R11114

Tegelijkertijd zorgde de best presterende vervangingskatalysator voor een reductie van de NO_x emissies in de stad van 30 mg/km, ofwel 90% reductie ten opzichte van de originele katalysator. De NO_x emissies van de vervangingskatalysatoren lieten een grote spreiding zijn, zowel tussen de verschillende merken als tussen verschillende exemplaren van hetzelfde type. Het laat zien dat er voldoende betaalbare alternatieven op de markt zijn die uitstekend presteren, maar voor de consument niet te onderscheiden zijn van de modellen die sterk verhoogde NO_x emissies hebben.

Praktijkemissies en APK voor gemodificeerde voertuigen

Een driewegkatalysator is een effectieve manier om de uitstoot van benzinevoertuigen te verlagen, maar is afhankelijk van een goede werking van de katalysator en een goede regeling van het lucht-brandstof mengsel. Soms wordt omwille van motorvermogen, geluid of kostenbesparing een katalysator vervangen door een sportief exemplaar of zelfs geheel verwijderd waardoor afbreuk wordt gedaan aan de bedoelde goede werking van de katalysator. In een meetprogramma zijn daarom drie voertuigen getest om het effect van dergelijke modificaties op de NO_x emissies te bepalen. Ook is onderzocht of dergelijke modificaties worden gedetecteerd door de APK test. Er zijn metingen gedaan aan een Renault Twingo met een race-katalysator, een Volkswagen Polo en een BMW 318ti, waarvan de laatste twee voertuigen getest zijn in zowel originele configuratie als zonder katalysator. De testresultaten lieten zien dat de NO_x emissies sterk verhoogd werden in het geval van de aanpassingen. De Twingo met race-katalysator had een toename in de NO_x emissies van bijna achtmaal de Euro 4 limietwaarde, terwijl de voertuigen zonder katalysator een toename in de NO_x emissies hadden van 15 tot 51 maal die in de originele configuratie, ofwel een toename van tussen de 2,3 en 3,1 g/km. Op basis van deze emissieresultaten kunnen deze voertuigen worden aangewezen als zogeheten high emitters, maar bij een APK test blijkt dit niet zo eenduidig. Twee van de drie voertuigen slaagden voor de EOBD testen, dus voor de APK test, één gaf een emissiegerelateerde storing in het boorddiagnosesysteem en deze slaagde vervolgens ook niet voor de CO-test. Al met al zou dus één van deze drie flink gemodificeerde voertuigen in de huidige APK afgekeurd worden. Het testprogramma gaf bovendien een beeld van het NO_x emissiegedrag van de voertuigen waarmee onderzocht kan worden of een APK test de voertuigen met modificaties met een sterke verhoging van de NO_x emissies detecteert. Zo is er voor de Twingo met race-katalysator slechts een zwak verband tussen de NO_x emissies tijdens stationair draaien zoals bij de APK test (NO_x is laag) en rijden op de weg (NO_x is hoog). Met een stationaire APK test zullen voertuigen die op de weg hoge NO_x emissies hebben dus niet altijd goed gedetecteerd kunnen worden. Het doel van de APK testen is het detecteren van voertuigen met hoge emissies op de weg. De mogelijkheden hiervoor worden hierna samengevat.

De significant verhoogde NO_x emissies op de weg van de voertuigen met zowel de vervangingskatalysatoren als ook de sportieve modificaties onthullen een mogelijke verborgen grote emissiebron in het Nederlandse benzinewagenpark zoals vastgelegd in de emissiefactoren. Aanvullend onderzoek naar voertuigen met significant verhoogde emissies in het benzinewagenpark wordt sterk aanbevolen.

Mogelijkheden voor verbeterde detectie van benzinevoertuigen met sterk verhoogde NO_x emissies

Zes mogelijkheden voor verbeterde detectie van voertuigen met sterk verhoogde NO_x emissies, ook wel high emitters genoemd, in de benzinevloot zijn hieronder beschreven en voor zover mogelijk geëvalueerd:

- Het invoeren van een strengere voertuigopwarmingsprocedure voor de uitlaatgastest in de APK test zal leiden tot een verhoogde detectie van voertuigen met hoge uitstoot (high emitters).
  Dit voorkomt dat voertuigen die alleen met kunstmatig verhoogde uitlaatgastemperaturen onder de gestelde APK limieten komen, onterecht worden goedgekeurd. Eventuele high emitters die geen verhoogde stationaire CO emissies laten zien, blijven echter ongedetecteerd. Verder zal het verplicht stellen van de uitlaatgastest de kans op detectie van high emitters verhogen.

- Het invoeren van een smaller lambdavenster, van 0.99 tot 1.01, zal leiden tot een verhoogde kans op detectie van high emitters met een slechte mengselregeling.
  De kans dat gemodificeerde voertuigen, zonder katalysator of met racekatalysator worden gedetecteerd, zal hiermee mogelijk niet veel mee toenemen.

- Het invoeren van een verplichte EOBD test kan leiden tot verhoogde detectie van high emitters, hoewel het exacte resultaat en de effectiviteit moeilijk op voorhand zijn in te schatten. Er is een risico dat voertuigen met normale emissies worden afgekeurd, met als gevolg dat er een voorkeur voor bepaalde merken en modellen ontstaat die over een zwakker intern boorddiagnosesysteem beschikken en mogelijk zelfs stimuleren om dit systeem te manipuleren.

- Het invoeren van een 5-gas test (het uitbreiden van de 4-gas meting voor de uitlaatgastest met een NO_x meting) zou een kleine uitdaging zijn op het gebied van meetapparatuur. Het definiëren van een eenvoudige en effectieve NO_x test en bijbehorende limieten is mogelijk veel lastiger. Op basis van de meetresultaten lijkt er bijvoorbeeld weinig samenhang tussen de NO_x emissies tijdens een APK uitlaatgastest en de NO_x emissies op de weg.

- De eerste resultaten van de stationaire testen met een koude start zijn veelbelovend. Aanvullend onderzoek is echter nodig om te effectiviteit van een dergelijke test te bepalen.

- Door middel van pluimmetingen van verkeer op de belangrijkste wegen in Nederland kunnen high emitters in de benzinevloot gedetecteerd worden en voertuiggegevens opgeslagen worden voor latere opvolging. Aanvullend onderzoek is nodig om de effectiviteit van deze nieuwe methode te bepalen. Ook is de methode geschikt om de ontwikkelingen van de NO_x emissies van de vloot te kunnen monitoren.

Aanbevelingen voor verbeterde detectie van benzinevoertuigen met sterk verhoogde NO_x emissies

Op basis van een eerste evaluatie van de mogelijkheden voor verbeterde detectie van voertuigen met sterk verhoogde emissies in de benzinevloot, zijn onderstaand de geselecteerde opties ingedeeld in twee categorieën.

Maatregelen met beperkte veranderingen ten opzichte van huidige APK methodiek
Indien de wens is om zo dicht mogelijk bij de huidige APK methodiek te blijven, zijn er drie opties die de mogelijkheid voor detectie van high emitters verhogen, maar slechts in geringe mate. De drie mogelijkheden betreffen de opwarmprocedure voor de uitlaatgas test, het verplichtstellen van deze test en versmallen van het lambdavenster.

Maatregelen waarvoor aanvullend onderzoek benodigd is
Er zijn twee opties die verder weg liggen van de huidige APK methodiek, maar die veelbelovende eerste resultaten laten zien voor het detecteren van high emitters:
de koude-start test en het doen van pluimmetingen aan voertuigen op de weg. Beide opties vragen vervolgonderzoek.

Summary

Earlier investigations[3,4], conducted by TNO on behalf of the Ministry of Infrastructure and Water Management showed that the Dutch fleet contains petrol vehicles that have significantly elevated NOx emissions. Following this, follow-up research was conducted within the programme-based cooperation between the Ministry of Infrastructure and Water Management and TNO on vehicle emissions. The aim of this was to gain more insight into the share of these vehicles in the fleet, the level of emissions from these vehicles on the road and to explore possibilities for better detection of vehicles with elevated NO_x emissions. This study consists of four parts around the same theme. The results are summarised in this report.

Characterisation of fleet NO_x emissions by plume-chasing
In previous research, vehicle emissions were extensively tested on an individual basis and while this provided a detailed insight into the emission behaviour of each vehicle measured, it did not provide a sufficient statistical basis for determining the impact of the measured vehicles with elevated NO_x emissions on the total. TNO therefore developed a new method for performing plume measurements on the road and deployed this method during this study. Plume measurement is a form of 'remote measurement'. For measurements of vehicles on public roads, a vehicle is specially equipped with instruments to measure the emissions of many vehicles in a short time, the sniffer van.

The results of 120 passenger vehicles measured provides a first insight into the NO_x emissions of petrol and diesel vehicles in the Dutch fleet. The first results confirmed the expectation that NO_x emissions increase with mileage, but also that there is a large spread of NO_x emissions in vehicles with low mileage. However, this is an intermediate result; the sniffer bus will be deployed in 2024 to measure more vehicles with this special method.

The effects of catalytic converter theft and replacement on NO_x emissions
In the Netherlands, the Toyota Prius, and its similar vehicles of the brand, is the biggest victim of catalytic converter theft. For catalytic converter replacement, there are several options with varying prices. For the owner, it may be more attractive to opt for a cheaper non-original replacement catalytic converter. The question is how these replacement catalysts perform with regard to NO_x emissions in practice. A measurement programme was carried out to get a first picture. For this purpose, a second-generation Toyota Prius with both the original catalytic converter and five non-original alternatives was subjected to on-road emission tests.

The results showed that replacing the catalytic converter could lead to an increase in urban NO_x emissions of 1,200 mg/km, or 34 times the emissions with the original catalytic converter. At the same time, the best-performing replacement catalytic converter provided a reduction in urban NO_x emissions of 30 mg/km, or 90% reduction compared to the original catalytic converter. NO_x emissions from the replacement catalysts showed a widespread, both between different brands and between different units of the same type.

[3] On road emissions of 38 petrol vehicles with high mileages, TNO report 2020 R11883
[4] Emissions of twelve petrol vehicles with high mileages, TNO report 2018 R11114

It shows that there are plenty of affordable alternatives on the market that perform excellently, but are indistinguishable to consumers from the models that have greatly increased NO_x emissions.

Real-world emissions and Periodic Technical Inspection of vehicles with aftermarket race catalysts

A three-way catalytic converter is an effective way to reduce emissions from petrol vehicles, but depends on the catalytic converter working properly and controlling the air-fuel mixture properly. Sometimes, for the sake of engine power, noise or cost savings, a catalytic converter is replaced with a sporty one or even removed altogether, thus compromising the intended proper functioning of the catalytic converter. A measurement programme therefore tested three vehicles to determine the effect of such modifications on NO_x emissions. It was also investigated whether such modifications are detected by the PTI test. Measurements were made on a Renault Twingo with a racing catalytic converter, a Volkswagen Polo and a BMW 318ti, the latter two vehicles being tested in both original configuration and without a catalytic converter.

The test results showed that NO_x emissions were greatly increased in the case of the modifications. The Twingo with racing catalyst had an increase in NO_x emissions of almost eight times the Euro 4 limit value, while the vehicles without catalyst had an increase in NO_x emissions of between 15 and 51 times that in the original configuration, or an increase of between 2.3 and 3.1 g/km.

Based on these emission results, these vehicles could be designated as so-called high emitters, but in a PTI test, this does not appear to be so unambiguous. Two of the three vehicles passed the EOBD tests, thus passing the PTI test, one gave an emissions-related fault in the on-board diagnostic system and it subsequently failed the CO test as well. All in all, therefore, one of these three substantially modified vehicles would be rejected in the current PTI.

The test programme also provided a picture of the NO_x emission behaviour of the vehicles that can be used to investigate whether a PTI test detects the vehicles with modifications with a sharp increase in NO_x emissions. For example, for the Twingo with racing catalyst, there is only a weak correlation between NO_x emissions during idling as in the PTI test (NO_x is low) and driving on the road (NO_x is high). Thus, with an idling PTI test, vehicles that have high NO_x emissions on the road will not always be detected properly. The aim of PTI testing is to detect vehicles with high emissions on the road. The possibilities for this are summarised below.

The significantly increased on-road NO_x emissions from the vehicles with both replacement catalysts and also sport modifications reveal a possible hidden major emission source in the Dutch petrol car fleet as recorded in the emission factors. Additional research on vehicles with significantly increased emissions in the petrol car fleet is strongly recommended.

Options for improved detection of petrol high emitters

Six options for improved detection of vehicles with greatly increased NO_x emissions, also known as high emitters, in the petrol fleet are described below and evaluated to the extent possible:

- Introducing a more stringent vehicle warm-up procedure for the exhaust gas test in the PTI test will lead to increased detection of high-emission vehicles (high emitters).

This will prevent unjustified approval of vehicles that fall below the set PTI limits only with artificially raised exhaust gas temperatures. However, any high emitters that do not show increased stationary CO emissions will remain undetected. Further, making the exhaust gas test mandatory will increase the chances of detecting high emitters.

- Introducing a narrower lambda window, from 0.99 to 1.01, will lead to an increased chance of detecting high emitters with poor mixture control. This may not significantly increase the likelihood of detecting modified vehicles, without catalysts or with racing catalysts.

- Introducing a mandatory EOBD test may lead to increased detection of high emitters, although the exact result and effectiveness are difficult to estimate in advance. There is a risk of vehicles with normal emissions being rejected, resulting in a preference for certain makes and models that have a weaker internal on-board diagnostic system and possibly even encouraging manipulation of this system.

- Introducing a 5-gas test (extending the 4-gas measurement for the exhaust gas test to include a NO_x measurement) would be a minor challenge in terms of measuring equipment. Defining a simple and effective NO_x test and associated limits may be much more difficult. For example, based on measurement results, there seems to be little correlation between NO_x emissions during a PTI exhaust gas test and on-road NO_x emissions.

- Initial results from cold-start stationary tests are promising. However, additional research is needed to determine the effectiveness of such a test.

- Through plume measurements of traffic on major roads in the Netherlands, high emitters in the petrol fleet can be detected and vehicle data stored for later follow-up. Additional research is needed to determine the effectiveness of this new method. The method is also suitable for monitoring trends in fleet NO_x emissions.

Recommendations for improved petrol high emitter detection
Based on an initial evaluation of options for improved detection of vehicles with greatly increased emissions in the petrol fleet, the selected options are classified into two categories below.

Measures with limited changes compared to current PTI methodology.
If the desire is to stay as close as possible to the current PTI methodology, there are three options that increase the ability to detect high emitters, but only slightly. The three options concern the warm-up procedure for the exhaust test, making this test mandatory and narrowing the lambda window.

Measures requiring additional research.
There are two options that are further away from the current PTI methodology but show promising initial results for detecting high emitters: the cold start test and plume chasing of vehicles on the road. Both options require follow-up research.

Contents

1 Introduction

Previous work has shown that the total emissions from the petrol fleet are significantly influenced by having a small share of high emitters among them [1], [2]: these high emitters, representing 6% of all tested petrol vehicles, were responsible for 36% of the total NO_x emissions. NO_x emissions of vehicles with a defective three-way catalytic converter can increase by a factor 10 or more compared to vehicles with well-functioning catalysts, but the statistical basis is small.

The current procedure in the Dutch PTI, which should detect and reject improperly functioning and high emitting vehicles, involves predominantly checking the EOBD and only if necessary, an additional exhaust gas emissions test [3] is to be conducted. Recent work has highlighted the ineffectiveness of the current PTI method in detecting high emitters and has made recommendations for potential improved and alternative procedures [4]. Effective measures for detecting NO_x high emitters and being able to force repair or removal from the fleet, are essential in reducing the NO_x emissions of the fleet in the long term.

This report contains a summary of four investigations on different topics related to the issue of on-road NO_x emissions of the Dutch petrol fleet and the share of high emitters among it (chapter 2), the effects of catalytic converter replacement on petrol vehicle NO_x emissions (chapter 3), the effects of vehicle modification and catalytic converter removal on on-road petrol vehicle NO_x emissions and PTI emissions testing performance (chapter 4) and possibilities for improved detection of NO_x high emitting petrol vehicles (chapter 5).The common thread of this work is the presence of NO_x high emitters in the fleet, characterizing the magnitude and impact of these high emitters, and looking into effective options for detection and reduction of NO_x high emitters.

This research has been performed as part of the programmatic collaboration between the Ministry of Infrastructure and Water Management (IenW) and TNO.

2 Measuring fleet emissions using plume chasing

This chapter revolves around characterisation of the fleet emissions and improving the estimation of high emitters among it. The current statistic for the amount of high emitters in the Dutch fleet is estimated at 6% for petrol vehicles. Traditionally this has been established using extensive emission testing of one vehicle at a time. This method provides detailed insight into the emissions behaviour of a specific vehicle but often requires multiple days of work, including vehicle instrumentation and testing. Plume chasing provides a less detailed but much faster method for measuring on-road NO_x emissions of a vehicle as it typically only needs around 5 minutes of measuring without instrumenting the vehicle.

Plume chasing is a form of remote sensing with a measurement vehicle equipped with NO_x and CO_2 measurement devices normally used for air quality measurements, together with a radar and license plate camera. On the front of the vehicle there are two inlets that transport the captured plume to the measurement devices in the rear cabin. Pictures of the TNO plume chase vehicle are in Figure 2.1. The emissions measurement is performed by driving behind a vehicle of interest, i.e. chasing, and capturing their exhaust gasses, i.e. plume. After a few minutes of chasing, an estimation of the on-road NO_x emissions of the vehicle can be calculated. Keep in mind that the emissions plume cannot be captured in its entirety with this method as the exhaust gas is severely diluted by ambient air, so the raw measurement data only provides concentrations of the gasses in the sampled plume. However, by continually observing the ratio between gaseous concentrations in both the background and the vehicle's plume, the actual concentrations of the pollutants from the tail-pipe can be accurately estimated. Furthermore, by augmenting the gaseous measurements with vehicle information absolute emission totals in g/km are calculated. The effectiveness of this method for detecting manipulation on diesel vehicles has already been shown in the European CARES project [5]. Using the plume chaser for detecting high emitters will be further discussed in chapter 5.

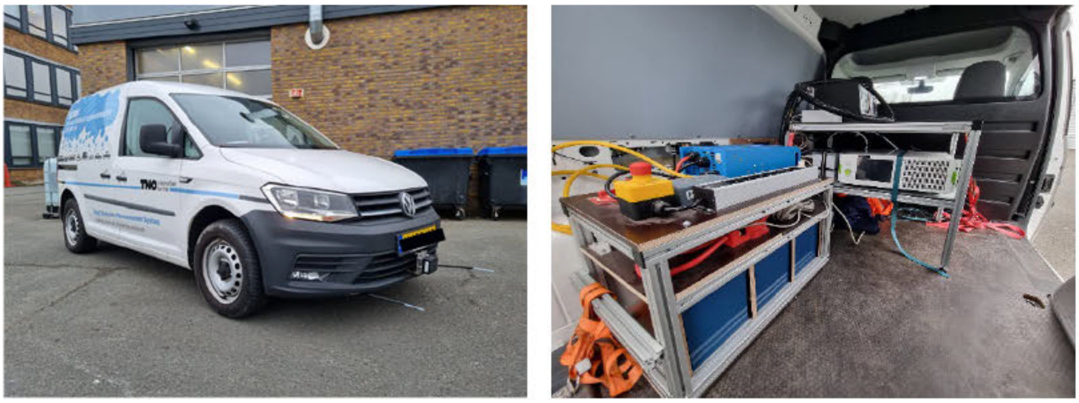

Figure 2.1: The inlets and radar on the front bumper and the license plate camera behind the window (left), and the measurement equipment and battery pack in the rear cabin (right) of the TNO plume chase vehicle.

The TNO plume chaser has thus far measured 120 passenger cars and light vans in the fleet on Dutch motorways and rural roads. Of these vehicles 83 were petrol and 37 were diesel. The results have been split up into two groups: diesel and petrol vehicles. Figure 2.2 shows the results for the diesel vehicle measurements. A large share of vehicles showed emissions below 600 mg/km, of which the biggest share has emissions below 200 mg/km and a very small share of much higher emitters well above 600 mg/km.

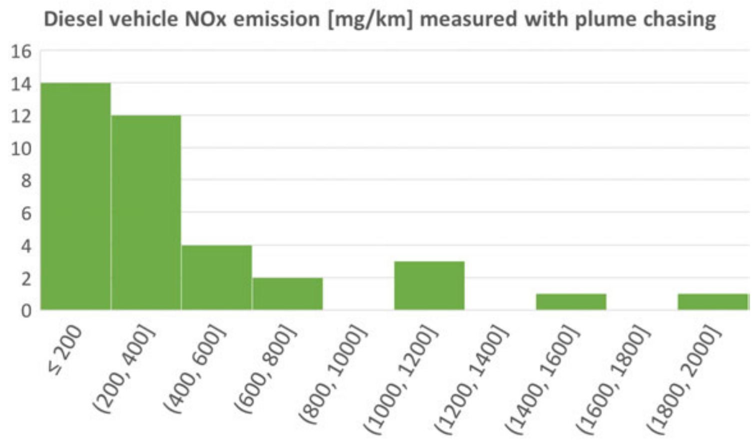

Figure 2.2: Plume chasing NO_x emission results for diesel LD vehicles, the horizontal axis represents the emission factor in mg/km.

In Figure 2.3 the NO_x emissions based on the plume chasing present a much flatter spread over the first four bins, which go up to 300 mg/km, with a small tail up going to around 800 mg/km. These results are considered preliminary as the amount of measured vehicles is limited.

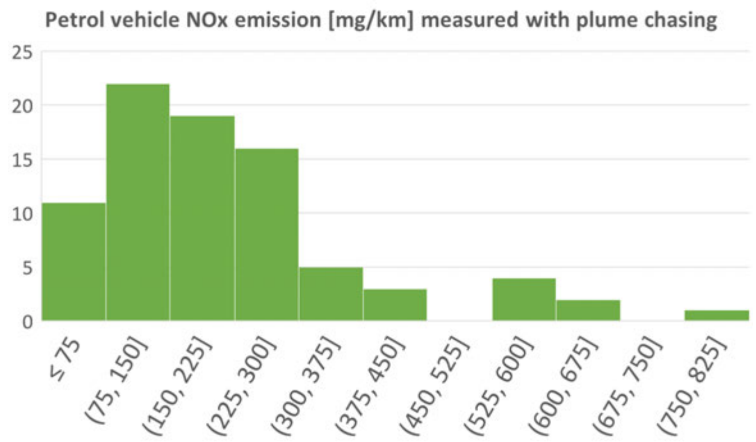

Figure 2.3: Plume chasing NO_x emission results for petrol LD vehicles, the horizontal axis represents the emission factor in mg/km.

The results of the plume chased petrol vehicles have also been used for further insight into the effect of ageing on NO_x emissions. Emission results have been combined with odometer reading registrations to relate on-road emissions to vehicle mileage.

The first results showed an expected increase in NO_x emissions with increased mileage, although the low mileage vehicles contained significant amounts of high emission vehicles, more than previously estimated. There is a large spread of the NO_x emissions, also for newer vehicles as shown in Figure 2.4.

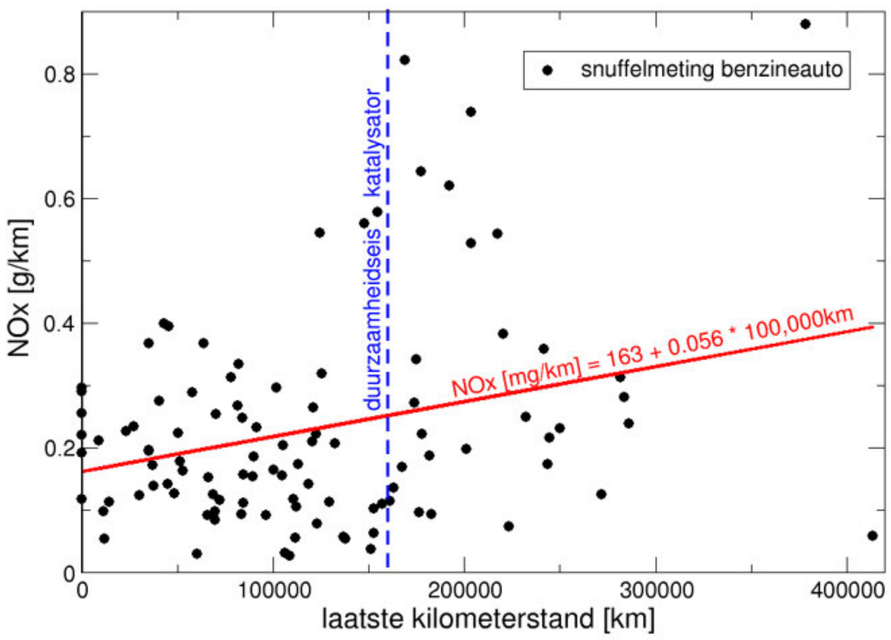

Figure 2.4: On-road NO_x emissions of petrol vehicles measured by the plume chase car as a function of mileage. These first measurements show a large spread and a trend of NO_x emissions on average becoming higher at higher mileage, but the correlation is weak.

These measurements provide a first insight into estimations of the on-road NO_x emissions of the fleet and are used to be taken into account to update national statistics such as emissions inventories [6]. Further analyses will be done and measurements in 2024 will expand the dataset and strengthen the fleet emissions statistics.

3 Catalytic converter theft and replacement

In this chapter the results of a research study on the emissions of a vehicle equipped with an original and various replacement catalytic converters are presented. The main objective of this work is to characterise the effects of catalytic converter replacement after theft and/or replacement of the original catalytic converter on the road emissions of the respective vehicles.

In the Netherlands, the Toyota Prius and other vehicles with the same drivetrain and aftertreatment are the most popular victims of catalytic converter theft.
In 2021, 3,379 catalytic converters were stolen, of which 1,388 from a Toyota Prius, based on insights from LIV[5]. When replacing the catalytic converter, there are many options at various price points within the market and it might be more attractive for the vehicle owner to replace it with a (cheaper) aftermarket one instead of the original.

3.1 Testing parameters

With a desk study roughly three categories for a replacement catalytic converter for the Prius were found: (near-)OEM with a price of around € 1.000. midrange with a price of around € 600 and budget with a price below € 300. Based on the aforementioned information, a second-generation Toyota Prius was selected as a test vehicle and an on-road emission test programme was performed containing the following catalytic converters:

Table 1: A list of the catalytic converters measured on the Toyota Prius under on-road conditions.

No.	Type	Brand	Condition
1	Original (OEM)	Toyota	Unknown
2	Midrange	Bosal	New
3	Budget	Uitlaatdiscounter	New
4	Midrange, incl. cert.	BM	New
5	Budget #2	Uitlaatdiscounter	New
6	Midrange #2	Bosal	New

[5] https://www.automotive-online.nl/management/overig/2022/01/05/liv-recordaantal-katalysatoren-gestolen-in-2021/

Figure 3.1: The Toyota Prius test vehicle equipped with PEMS test equipment ready for on-road testing

Each catalytic converter was installed on the vehicle at a garage and followed by a running-in period of more than 200 km of driving. Emissions were tested on-road using a PEMS system with an RDE (Real Driving Emissions) style route of around 85km under normal driving behaviour. The vehicle in original configuration had a NO_x emission result of 16 mg/km, which is a respectable value considering the Euro 4 limit of 80 mg/km and the high vehicle mileage of over 360,000 km. Important to note here that the mileage on the original catalytic converter is unknown as it was already on the vehicle at the start of the measurement campaign and full-service history was not available.

3.2 On-road NO_x emission results

As the test vehicle is a hybrid, the usage of the combustion engine not only depends on the driver's inputs, but also on vehicle parameters such as battery state of charge. The amount of work the combustion engine performs during the on-road test cycle is less consistent than with a non-hybrid petrol vehicle. Therefore the emission results from the PEMS were further analysed before comparing emissions performance of each configuration. From the PEMS results, the NO_x, CO_2 and vehicle speed data were used to construct Augmented Emission Maps (AEMs) of each configuration. AEMs give insight into the emissions characteristics and allow to predict the NO_x emissions of the vehicle given certain conditions, as can be seen in Figure 3.2. Combining these AEMs with driving data from all six tests (as discussed in Appendix **A.1.1**), reveals emissions results per configuration that are directly comparable.

Figure 3.2. shows a clear difference between the emission characteristics of the OEM and Midrange incl. cert. catalysts and the other four catalysts. For both the two midrange and the two budget catalysts higher NO_x emissions occur at CO_2 emissions above 1 g/s i.e. as soon as there is some degree of acceleration. Furthermore, the OEM and Midrange incl. cert. catalysts show clear regions of lower NO_x emissions between 40 – 60 km/h which highlights the impact that the different configurations can have in urban settings.

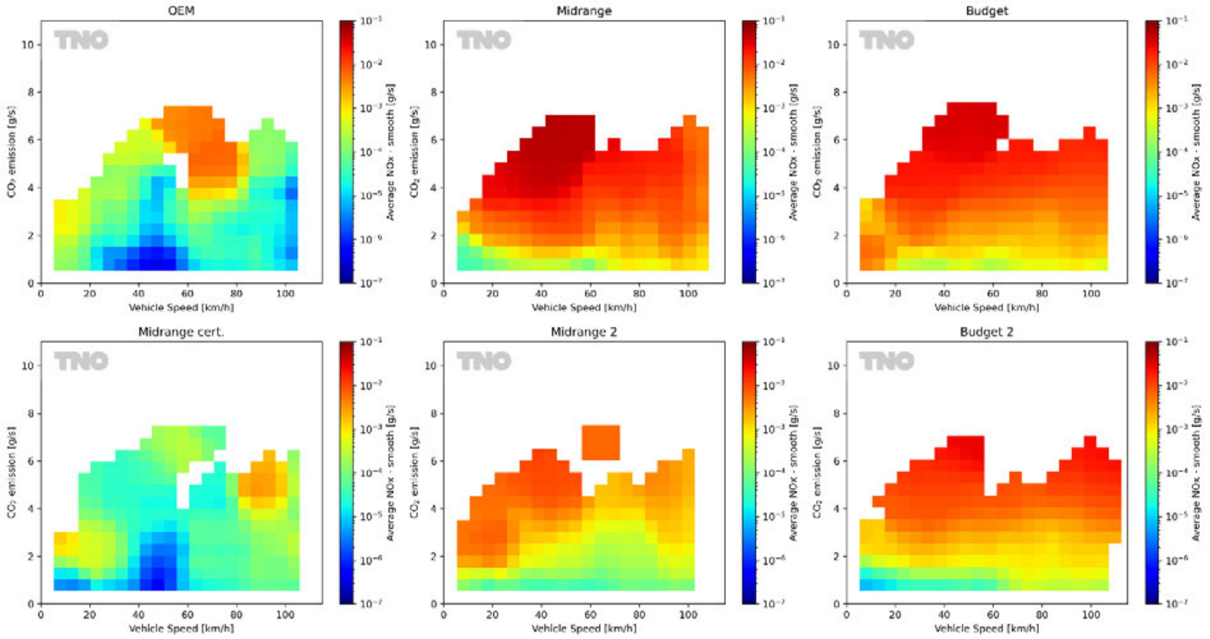

Figure 3.2: Emission maps of the NO_x emissions as a function of CO_2 and speed, of the Toyota Prius per catalyst configuration. Red indicates higher NO_x emissions; the localisation of these higher emissions demonstrates differences in catalytic function.

In the figure below the NO_x results are plotted for each road type and each configuration, and in the table the exact values are presented. The right side of the table shows the NO_x results per configuration compared to the performance with the original catalytic converter.

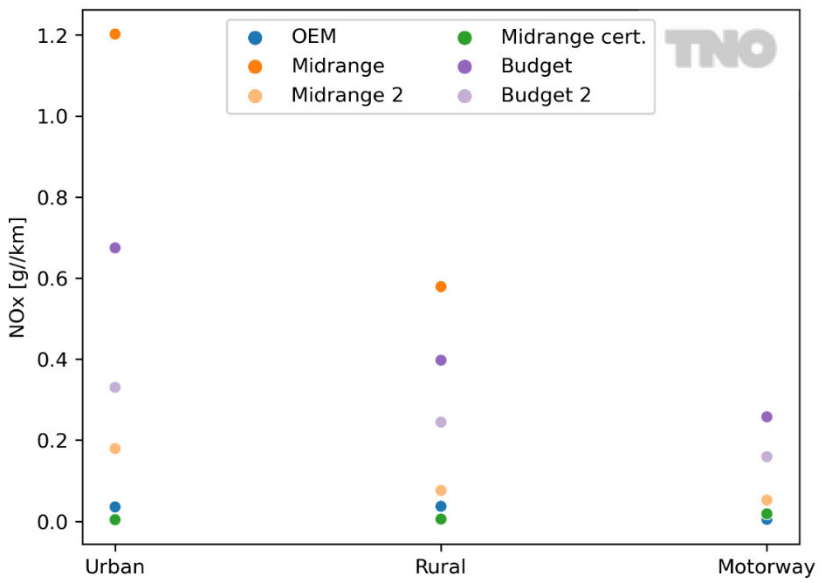

Figure 3.3: NO_x emissions of a petrol vehicle equipped with various catalytic converters, displayed per road type.

Table 2: NO_x emissions of a petrol vehicle equipped with various catalytic converters, categorized per road type (left) and compared to OEM (right).

NOx emissions	**Urban**	**Rural**	**Motorway**		Factor over OEM	**Urban**	**Rural**	**Motorway**
OEM	35.4	36.8	4.7	*mg/km*		1.0	1.0	1.0
Midrange	1202.2	579.0	259.0	*mg/km*		34.0	15.7	55.1
Midrange 2	179.2	76.1	52.3	*mg/km*		5.1	2.1	11.1
Midrange cert.	3.8	5.3	18.4	*mg/km*		0.1	0.1	3.9
Budget	674.5	397.3	257.6	*mg/km*		19.1	10.8	54.8
Budget 2	330.4	244.6	159.4	*mg/km*		9.3	6.6	33.9

The results show a large scatter in NO_x emissions, most visible in the urban section. Here the worst performing catalytic converter has NO_x emissions of over 1200 mg/km, which is over 30 times the NO_x emissions of the original. The Midrange including certificate was the only catalytic converter to perform better than the OEM, except under motorway conditions.
The scatter also shows the significant difference in emission performance for both separate units of the midrange and the budget catalytic converters. In urban and rural conditions, the NO_x emissions of the worst performing example are upwards of 6.5 times and 1.6 times for the Midrange and Budget catalytic converter respectively. For urban conditions this results in an absolute increase of 1000 mg/km for the Midrange and 340 mg/km for the Budget catalytic converter. The results have been shared with the suppliers.

3.3 Conclusion

Although the dataset is limited to 6 configurations the results of the on-road emission measurements show that catalytic converter replacement, for example due to theft, can significantly increase the NO_x emissions of vehicles in the fleet. More importantly, the widespread in NO_x emissions between various catalytic converter types and examples shows that the aftermarket offers parts, well below OEM prices, capable of excellent NO_x reduction while simultaneously offering ones that increase NO_x emissions dramatically, seemingly indistinguishable from each other from a consumer perspective. Further research is recommended for looking into the variability in emissions of replacement catalysts and the possible root causes for this variation.

4 Vehicle modification: on-road and PIT emissions testing

In this chapter the results of a research study on the emissions of three vehicles with purposeful aftertreatment tampering and removal are presented. The main goal of this work is to characterise the effect of vehicle modification on both the on-road emissions and the emissions during PTI of the affected vehicles.

Reduction of the engine out NO_x emissions in petrol vehicles relies heavily on the presence of a three-way catalytic converter combined with proper control of the air-fuel ratio (lambda). Replacing the catalytic converter by a performance driven alternative or removing it entirely, can significantly impact the on-road NO_x emissions.

4.1 On-road emissions of three modified vehicles

(Figure 4.1) equipped, by the owner, with a performance oriented, high-flow catalytic converter and dyno tuning, a Volkswagen Polo and a BMW 318ti, which both have been tested in original configuration and after removing the catalytic converter. The vehicles were tested under stationary and on-road driving conditions and were started with a cold engine similar to real-world usage. The on-road testing was performed under normal driving behaviour, similar to that during an official RDE test. The route was over 140 kilometres to ensure a substantial occurrence of each of the various road types: urban, rural and motorway. The emissions results are presented in Table 3.

Figure 4.1: Renault Twingo instrumented with a PEMS system undergoing stationary testing with an additional 5-gas analyser (PTI 4-gas analyser + NO_x) sampling in the exhaust tip.

Table 3: Emission results from the measurement program with heavily modified vehicles.

Vehicle	Euro class	Configuration	NO_x on-road [mg/km]
Renault Twingo	4	Tuned, high-flow catalyst	630
Volkswagen Polo	4	Original	45
		Removed catalyst	2300
BMW 318ti	2	Original	220
		Removed catalyst	3300

The results of the Renault Twingo showed significantly elevated emissions of 626 mg/km with the high-flow catalytic converter compared to the type approval limit for Euro 4 of 80 mg/km. Assuming the Twingo originally produced NO_x emissions at the limit (which is a very safe assumption), this already translates into almost 8 times the NO_x emissions or an increase of 546 mg/km. The results of the Volkswagen Polo and the BMW 318ti are even higher. Removing the catalytic converter increased the on-road NO_x emissions by 15 to 51 times compared to the original configuration.

Figure 4.2 shows the effect of both types of modifications on the emissions behaviour under various conditions. The Renault Twingo has relatively comparable emission behaviour at CO_2 emissions below 1.5 g/s when compared to the original states of the Volkswagen Polo and the BMW 318ti, but has higher emissions when accelerating and at higher speeds. This shows that there is a catalytic converter present in the exhaust system of the Twingo, but an undersized one incapable of reducing NO_x emissions under real-world occurring higher exhaust flow conditions. The mostly dark red emission maps for the vehicles in removed catalytic converters configuration show that high emissions occur in all situations, except at very low speeds and acceleration.

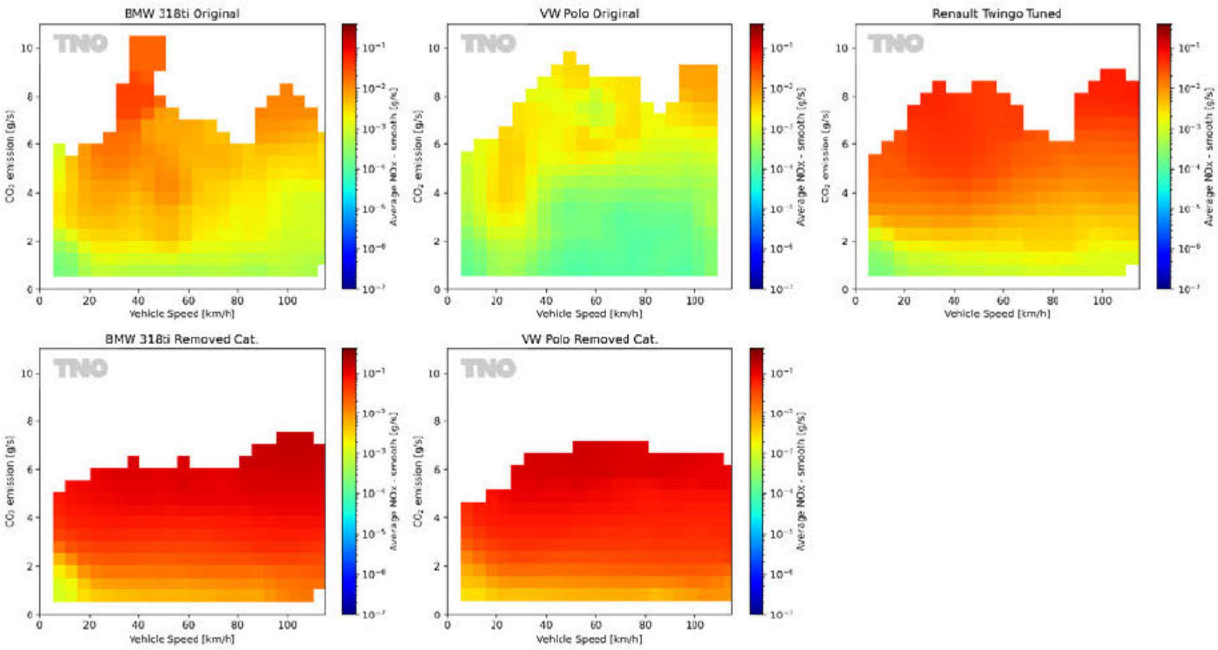

Figure 4.2: NO_x emission maps for the three modified vehicles, where NOx is shown as a function of CO_2 and speed. Red indicates higher NO_x emissions; the localisation of these higher emissions highlights the effects of the modifications.

The vehicles with removed catalytic converters present a near worst case scenario in terms of NO_x emissions and provide a useful opportunity for testing the current measures such as the PTI emissions test for recognizing such as extreme cases.

4.2 Emissions in PTI

The current PTI procedure for newer petrol vehicles in the Netherlands (APK- Algemene Periodieke Keuring, APK2, Artikel 5.2.11[6]) involves EOBD testing and when that is unsuccessful an exhaust gas test must be performed. A successful EOBD test can thus approve a vehicle regarding emissions and only the exhaust gas test can reject a vehicle, as can be seen in the APK Stroomschema EOBD [7].

The EOBD procedure APK2 5.*.11 is deemed unsuccessful when:

- The Malfunction Indication Light (MIL) is not present or not working.
- One or more aftertreatment P-codes are active.
- OBD readiness is incomplete.
- OBD connection cannot be established.

The exhaust gas test is performed with a warm engine, where the vehicle is measured stationary under normal engine idling and high idling between 2000 and 3200 rpm. A 4-gas analyser is used to measure the CO concentration in the exhaust and lambda to check for compliance with the designated limit values (Table 4).

Table 4: PTI emissions test limit values for CO and Lambda.

	PTI limit	
	CO [%vol]	Lambda
Idle	0.3	-
High idle	0.2	0.97 - 1.03

The NO_x emissions measured during on-road testing of the three modified vehicles are significantly elevated due to the changes in the aftertreatment system and can be considered severe high-emitters. However, just by looking at the results from the PTI procedure, the modified vehicles are not (simply) recognized as such.

Starting with the OBD check, the Renault Twingo and the BMW 318ti successfully finish the OBD test as there are no errors present, while the Volkswagen Polo fails on a catalytic converter efficiency P-code. Based on these results, the Renault and the BMW would have been approved without the need of an emission test.

Nevertheless, a 4-gas emissions test was performed with each vehicle and the emissions results are shown in Table 5. The CO values of the vehicles from which the catalytic converters have been removed are above the PTI limit, while the lambda values of all three modified vehicles are on target. The Renault Twingo, with more than 7 times higher on-road NO_x emissions than original, performs close to perfect with a lambda of 1.00 and CO values up to 0.03 %vol. The high-flow catalytic converter is very poor in reducing NO_x emissions on-road, yet it succeeds in reducing CO emissions during the stationary PTI emissions test.

[6] https://apk-handboek.rdw.nl/personenautos/motor/geluid-en-milieu

Table 5: Emission values of the modified vehicles during stationary PTI emissions test at idle and high-idle.

	Renault Twingo		Volkswagen Polo	BMW 318ti		
	CO [%vol]	Lambda	CO [%vol]	Lambda	CO [%vol]	Lambda
Idle	0.02	1.00	0.5	1.01	0.6	1.01
High idle	0.03	1.00	0.7	1.01	0.6	1.00

The poor NO_x reduction is visible on the time-based 5-gas analyser data during high idle conditions (Figure 4.3) where the NO_x concentration increases from 0 to fluctuating around 100 ppm.

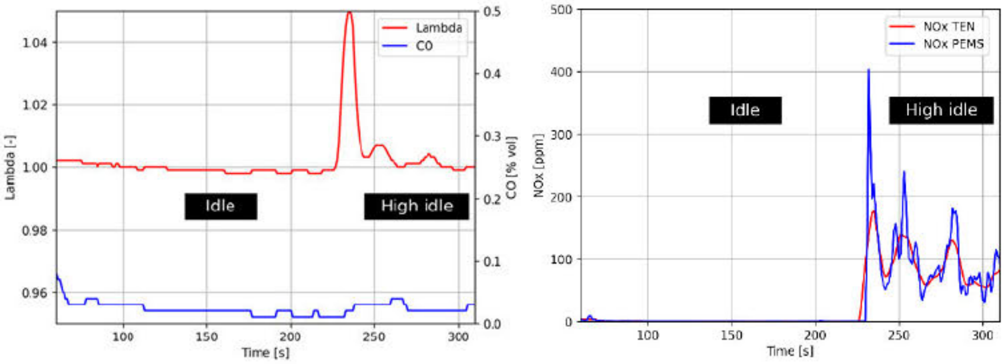

Figure 4.3: Raw data from the 5-gas analyser during a stationary PTI test of the Renault Twingo, on the left is CO in blue and Lambda in red, on the right is NO_x measured with PEMS and a TEN 5-gas tester.

The results of these measurements show that the current PTI procedure is unable to detect and reject the Renault Twingo with a high-flow catalytic converter. The other two vehicles without catalytic converter aren't detected using EOBD so in principle are approved. Only using the CO measurement of the 4-gas emissions test the vehicles can be detected and rejected.

The results from the high-flow catalytic converter also show the paradox of passing the emissions test while performing poorly at reducing (NO_x) emissions during real-world driving. More importantly, as long as a vehicle successfully passes the EOBD test no further emissions test is needed. These results show that improved PTI methods are needed for the detection of NO_x high emitters in the fleet and rejection of their roadworthiness until these vehicles are repaired or brought in original condition.

5 Possibilities for detection of NO_x high emitters of petrol cars in the fleet

For petrol vehicles, the current PTI emission test involves analysing exhaust gases at both low and high idle engine speeds. This analysis measures the concentrations of the 4 gases CO_2, CO, THC, and O_2. The lambda value, calculated at high idle speed, must fall between 0.97 and 1.03. Additionally, there are specific CO limit values for both idle speeds. Measuring NO_x emissions is not required. With EOBD tests (as an alternative to the exhaust gas analysis or the smoke opacity test or PN test) vehicles can undergo PTI by having their electronic on-board diagnostic system (EOBD) read for certain fault codes. EOBD systems monitor the status of hardware (sensors and actuators) and some engine behaviours through software. When malfunctions occur, fault codes are stored in the electronic control unit (ECU). This EOBD test can approve a vehicle regarding its emissions but not reject it. The exhaust gas test is decisive and can reject a vehicle.

The procedure for petrol vehicles is a straightforward test covering a limited area of the engine map. Fortunately, most petrol vehicles have good emission performance due to the robust and mostly durable three-way catalyst technology. However, a percentage of high-emitting petrol vehicles contribute disproportionately to overall traffic pollution, including high NO_x emissions [1], [2]. Implementing a NO_x test could further improve the PTI for petrol vehicles.

A test should be able to classify a vehicle as high NO_x emitter and allow rejection of the vehicle to oblige vehicle owners to repair the malfunction which causes the high emission. This without false positives and as little false negatives as possible. In this chapter multiple options are discussed and evaluated for a test to detect NO_x high emitters. This is amongst other based on the available test results as discussed in chapter 4. The options for tests range from simple and cheap to complicated and costly.

5.1 Mandatory 4-gas emissions test and regulated test sequence

The simplest step of improvement is making the 4-gas emissions test compulsory during PTI testing, independent of the EOBD test results. The BMW 318ti and the Volkswagen Polo with a removed catalytic converter, as well as a Peugeot 206 from previous work showed significantly elevated CO emissions during the 4-gas emissions test while also showing well beyond 1000 mg/km in on-road NO_x emissions [1]. If the 4-gas emissions test was mandatory, these vehicles would be detected during PTI and rejected. It is important to consider that probably only a certain fraction of the high emitters is detected with this improved method, such as the ones tested without a catalyst and a race catalyst.

Both earlier work and the results of the Renault Twingo showed little correlation between on-road NO_x emissions and 4-gas CO levels, meaning a catalytic converter can perform poor at NO_x reduction while being successful at CO reduction during stationary emissions testing.

Previous work [1], [2], also showed the importance of the test sequence. A vehicle did not meet the CO limits under normal conditions, but had successfully passed the emissions test during an official PTI less than 12 months before. Since there is no limit on the preconditioning, vehicles with poor performing catalytic converters can be driven as hard as needed to warm up the exhaust system to a level that improves the catalytic conversion enough to succeed in the PTI emissions test. It is therefore important to regulate the test sequence to ensure proper evaluation of the stationary emission levels. Implementing a mandatory 4-gas emissions test combined with a regulated preconditioning of the vehicle would result in an increased detection of NO_x high emitters, although only a fraction of the high emitters can be detected since elevated on-road NO_x emissions do not necessarily correlate with elevated 4-gas CO levels.

5.2 Tightening limits for 4-gas emissions test

The window for the lambda value for high idle is currently defined between 0.97 and 1.03. The performance of the three-way catalyst is highly dependent on a properly oscillating lambda value. A predominantly lean air-fuel mixture often results in elevated NO_x emissions. Previous work with 38 petrol vehicles [1] showed that tightening this window to 0.99 - 1.01 would ensure detection and rejection of two high emitters, responsible for on-road emissions between 250 and 1,300 mg/km. Looking at the emission levels of the modified vehicles however, the impact is less apparent. All three of them have lambda between 1.00 and 1.01. Implementing the tightened lambda window would therefore result in an increase of detection of NO_x high emitters, but is limited in detecting modified vehicles.

5.3 Enforcing both OBD and 4-gas emissions test

The current PTI procedure can only approve a vehicle regarding its emissions based on the outcome of the EOBD test, but not reject it. If a vehicles passes the exhaust gas test, any unsuccessful EOBD outcome is disregarded and a vehicle is approved for the exhaust emissions. An option for improvement is to enforce successfully passing both the EOBD checks and the 4-gas emissions test. Although OBD is capable of self-diagnosing important engine and aftertreatment components, demanding successful passing of the EOBD checks does not guarantee an increase in NO_x high emitter detection. Previous work showed no correlation between high on-road NO_x emissions and passing the EOBD checks, as there were both high emitters that passed EOBD checks and normal emitters that did not pass the EOBD checks. Additionally, the underlying framework for the EOBD checks is not strictly defined and not required to be identical between vehicle brands and models. The EOBD fault codes that trigger a malfunction indication light (MIL) are regulated by defined OBD emission limits expressed in mg/km, as can be seen in Figure 5.1 below. However, the on-board evaluation of the vehicle emissions is only performed on a limited selection of all of the collected data, resulting in the real-world occurrences of exceeding OBD threshold limits without triggering OBD fault codes or a MIL. Implementing mandatory success of the EOBD checks may result in increased high emitter detection, but the exact effect and effectiveness cannot be determined beforehand. Additionally, there is a risk of rejecting normal emitting vehicles, thereby inadvertently favouring certain vehicle makes and models, and possibly stimulating (E)OBD manipulation.

Final Euro 6 OBD threshold limits

Category	Class	Reference mass (RM) (kg)	Mass of carbon monoxide (CO) (mg/km)		Mass of non-methane hydro-carbons (NMHC) (mg/km)		Mass of oxides of nitrogen (NO_x) (mg/km)		Mass of particulate matter (1) (PM) (mg/km)		Number of particles (2) (PN) (#/km)	
			PI	CI	PI	CI	PI	CI	CI	PI	CI	PI
M	—	All	1 900	1 750	170	290	90	140	12	12		
N_1	I	RM ≤ 1 305	1 900	1 750	170	290	90	140	12	12		
	II	1 305 < RM ≤ 1 760	3 400	2 200	225	320	110	180	12	12		
	III	1 760 < RM	4 300	2 500	270	350	120	220	12	12		
N_2	—	All	4 300	2 500	270	350	120	220	12	12		

Key: PI = Positive Ignition, CI = Compression Ignition.
(1) Positive ignition particulate mass and particle number limits apply only to vehicles with direct injection engines.
(2) Particle number limits may be introduced at a later date.

Figure 5.1: An overview of the Euro 6 OBD threshold limits. Regulation requires vehicle OBD to trigger a fault code when these emission limits are surpassed, although most vehicles do not have sensors to directly measure these emissions [8].

5.4 Changing the 4-gas emissions test into a 5-gas emissions test

The equipment used during the emissions test of the PTI is based on measuring four gases, namely CO, CO_2, O_2 and THC. CO (carbon monoxide) is measured to compare the test value to a limit value. The measurements of the four gases are used together to calculate the lambda value which has to fall within a specified bandwidth. Manufacturers of this equipment also supply a version capable of additionally measuring NO_x. This extra component could be useful for detecting NO_x high emitters because a properly functioning lambda control and catalytic converter should be capable of reducing NO_x concentrations under stationary conditions. However, previous reported work on emissions on twelve petrol vehicles has shown poor repeatability of the NO_x concentration levels under (high) idle as well as poor correlation between on-road NO_x emissions and idling NO_x concentrations.

In Figure 5.2 below the NO_x concentration behaviour is displayed for a vehicle with low on-road NO_x emissions (left) as well as one with significantly higher emissions (right), using data from earlier research [9]. The level of NO_x concentrations during idle and high idle stabilize around a similar level for both vehicles. This example shows that it would not be possible to deduce that the one on the right has over 15 times the on-road NO_x emissions compared to the one on the left, based on a short emissions test where the operator looks at stabilized NO_x values. Short duration events such as the peak in the right plot at 350 seconds are not taken into account since the PTI emissions test waits for stabilisation of emission values before making a verdict.

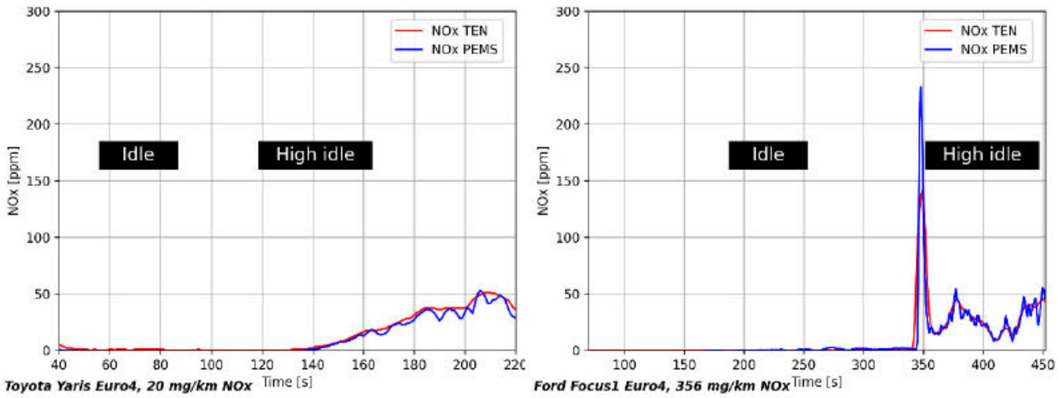

Figure 5.2: NO_x concentration during PTI emissions test displayed for a vehicle with low emissions (left) as well as a more than 15 times higher NO_x emitter (right). The height of the stabilized NO_x concentration levels under low and high idle are indistinguishable between left and right.

Implementing a 5-gas emissions test would require additional equipment to measure tail pipe NO_x concentrations. It will be highly complicated to define effective concentration limits for NO_x under idle and high idle conditions and based on the limited sample of tests, it is indicated that concentrations probably have a weak relation with normal driving.

5.5 Cold start emissions test

An alternative method to the 4-gas emissions test with a warm engine at idle and high -idle would be a cold start emissions test. The current stationary test with a warmed-up engine solely provides insight into stabilized aftertreatment behaviour. In the legislative NEDC, WLTP and the RDE test, the vehicle needs to have an appropriate heat-up strategy to ensure the vehicles meet the respective emission limits. The engine load is typically limited in these tests, idle also suffices, but the quality of the TWC (three-way catalyst) emission control strategy is most apparent in the heat-up period. A quick and effective emission reduction shows all aspects of the TWC technology function: a fast light-off time reaching high efficiency at low ambient temperatures, accurate mixture control, and the proper interaction with the engine settings and operation. Replicating these aspects in a PTI test, after a cold engine start, can cover and check the full functionality of the emission control technology.

The first results of cold start testing and analysis look promising, as can be seen in Figure 5.3 using data from earlier research [9]. In the plot on the left, a normal emitting vehicle shows a brief peak in NO_x concentration, while the plot on the right shows a significantly longer NO_x concentration peak as well as a long-sustained elevation.

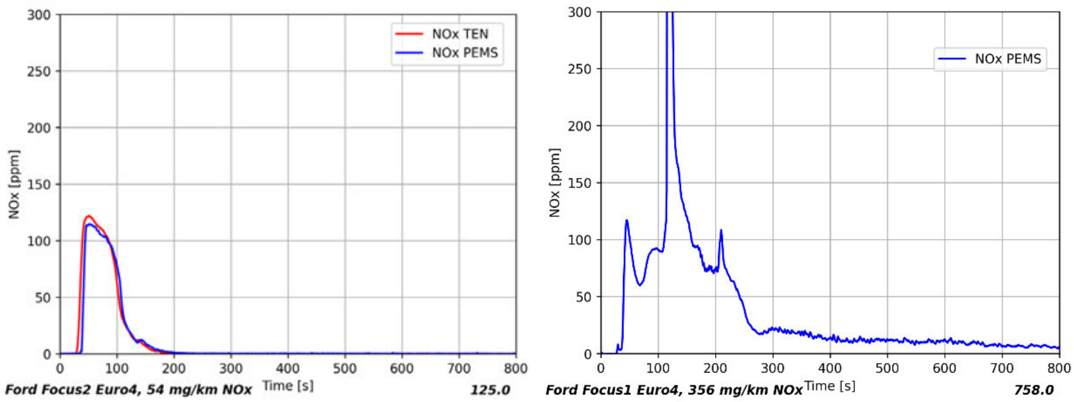

Figure 5.3: NO_x concentrations during stationary cold start test. On the left a normal emitting vehicle with on-road emissions of around 50 mg/km, on the right a high emitter with on-road emissions of around 350 mg/km. The right one shows a higher concentration peak and a longer sustained elevation.

The effectiveness of implementing cold start testing for detecting NO_x high emitters needs further investigation. Further analysis of cold start data by looking into NO_x, CO, CO_2, O_2 and Lambda behaviour under stationary cold start idling conditions. The expectation is to find fast emissions concentration reduction in low emitting vehicles under cold start.

5.6 On-road plume chasing

The most different method in this chapter for detecting NO_x high emitters is by using the novel method of plume chasing. The method and its results are described in chapter 2. Instead of measuring the emissions of a vehicle under stationary conditions and trying to correlate these to on-road emissions performance, with plume chasing NO_x emissions can be directly measured on the road. The effectiveness of implementing plume chasing for detecting NO_x high emitters in relation to PTI needs further investigation.

6 Conclusions and recommendations

The conclusions in this report have been divided into four sections: plume chasing for both petrol and diesel vehicles, petrol emissions measurements, detection of petrol NO_x high emitters and recommendations for improved high emitter detection.

Plume chasing

The results of plume chasing 120 light duty vehicles give a first insight into the on-road NO_x emissions of the diesel and petrol fleet.
A large share of the plume chased diesel vehicles showed emissions below 600 mg/km, of which the biggest share has emissions below 200 mg/km and a very small share of much higher emitters well above 600 mg/km.
The first results for the plume chased petrol vehicles showed an expected increase in NO_x emissions with increased mileage, although the low mileage vehicles contained significant amounts of high emission vehicles, more than previously estimated. There is a large spread of the NO_x emissions, also for newer vehicles. Plume chase measurements will be continued to increase the number of measured vehicles and for sound statistical underpinning of conclusions.

Petrol emissions and detection of NO_x high emitters

Catalytic converter replacement

The results of emission measurements done on a vehicle with the original catalyst and a number of available replacement catalysts which are available on the market showed a wide variation of the NO_x emissions between the different brands of catalysts and even between two different catalysts of the same type.
The worst performing replacement catalyst showed an increase in urban driving NO_x emissions to about 1200 mg/km, or 34 times the emissions of the original configuration, while the best one decreased the urban NO_x emissions by 30 mg/km, or 90% decrease compared to the original configuration. Also on the motorway the spread of NO_x emissions between the various catalysts is large.
The measurements showed excellent emissions reduction at the high mileage (well above 160 thousand kilometres) of the vehicle equipped with the original catalyst. Additionally, the widespread in NO_x emissions between various catalytic converter types and examples showed that the aftermarket offers parts, well below OEM prices, capable of excellent NO_x reduction while simultaneously offering ones that increase NO_x emissions dramatically, seemingly indistinguishable from each other from a consumer perspective.

Modified vehicles, on-road and PTI

The results of the modified vehicles measurement campaign showed that replacing the catalytic converter by a performance alternative or removing it altogether will significantly increase on-road NO_x emissions. The example with the performance catalytic converter showed an increase to almost eight times the Euro 4 NO_x emissions limit, while removing the catalytic converter increased the on-road NO_x emissions by 15 - 51 times compared to the original configuration.

Although from the on-road NO_x emissions these vehicles can undoubtedly be identified as high emitters, recognizing these NO_x high emitters as such within the current PTI framework isn't as evident. Two of the three vehicles cleared the OBD check and only one vehicle without catalytic converter revealed an emissions related P-code. The 4-gas emissions test showed almost perfect results for the vehicle with performance catalytic converter, while the other two showed close to perfect lambda values and elevated CO values above PTI limits. Only one of the three would have failed during PTI testing.

The Augmented Emission Maps (AEMs) give additional insight into the emissions behaviour, showing under which on-road conditions the highest NO_x emissions are present. The AEM of the tuned Renault Twingo further illustrates the weak link between NO_x emissions under idle conditions and under driving conditions. The AEM shows good NO_x emissions reduction performance for low CO_2 values, typically seen under idle or very low load driving conditions, while showing over a hundred times higher NO_x emissions for higher CO_2 values, typically seen with real-world driving conditions. The goal of the PTI testing is to detect vehicles that emit high emissions on the road under real driving conditions, and as such a robust detection method should incorporate emissions testing under loaded (or cold start) conditions, not only under hot idle.

The significantly elevated on-road NO_x emissions results of the vehicles equipped with a selection of the aftermarket replacement catalytic converters as well as the results of the tuned vehicle equipped with a high flow catalytic converter reveal a possibly hidden high emissions source within the Dutch petrol fleet. Further research into petrol NO_x high emitters is recommended.

Possibilities for improved petrol high emitter detection

Six options for improved detection of vehicles with greatly increased NO_x emissions, also known as high emitters, in the petrol fleet are described below and evaluated to the extent possible:

- Introducing a more stringent vehicle warm-up procedure for the exhaust gas test in the PTI test will lead to increased detection of high-emission vehicles (high emitters). This will prevent unjustified approval of vehicles that fall below the set PTI limits only with artificially raised exhaust gas temperatures. However, any high emitters that do not show increased stationary CO emissions will remain undetected. Further, making the exhaust gas test mandatory will increase the chances of detecting high emitters.

- Introducing a narrower lambda window, from 0.99 to 1.01, will lead to an increased chance of detecting high emitters with poor mixture control. This may not significantly increase the likelihood of detecting modified vehicles, without catalysts or with racing catalysts.

- Introducing a mandatory EOBD test may lead to increased detection of high emitters, although the exact result and effectiveness are difficult to estimate in advance. There is a risk of vehicles with normal emissions being rejected, resulting in a preference for certain makes and models that have a weaker internal on-board diagnostic system and possibly even encouraging manipulation of this system.

- Introducing a 5-gas test (extending the 4-gas measurement for the exhaust gas test to include a NO_x measurement) would be a minor challenge in terms of measuring equipment.

Defining a simple and effective NO_x test and associated limits may be much more difficult. For example, based on measurement results, there seems to be little correlation between NO_x emissions during a PTI exhaust gas test and on-road NO_x emissions.

- Initial results from cold-start stationary tests are promising. However, additional research is needed to determine the effectiveness of such a test.

- Through plume measurements of traffic on major roads in the Netherlands, high emitters in the petrol fleet can be detected and vehicle data stored for later follow-up. Additional research is needed to determine the effectiveness of this new method. The method is also suitable for monitoring trends in fleet NO_x emissions.

Recommendations for improved petrol high emitter detection
Based on an initial evaluation of options for improved detection of vehicles with greatly increased emissions in the petrol fleet, the selected options are classified into two categories below.

Measures with limited changes compared to current PTI methodology.
If the desire is to stay as close as possible to the current PTI methodology, there are three options that increase the ability to detect high emitters, but only slightly. The three options concern the warm-up procedure for the exhaust test, making this test mandatory and narrowing the lambda window.

Measures requiring additional research.
There are two options that are further away from the current PTI methodology but show promising initial results for detecting high emitters: the cold start test and plume chasing of vehicles on the road. Both options require follow-up research.

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Signature

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Appendix A
Additional analysis on-road measurements

In this section we present a number of extra analyses performed on the on-road measurements of the Toyota Prius with catalytic converter replacements, as well as the three modified vehicles.

A.1 Catalytic converter replacements

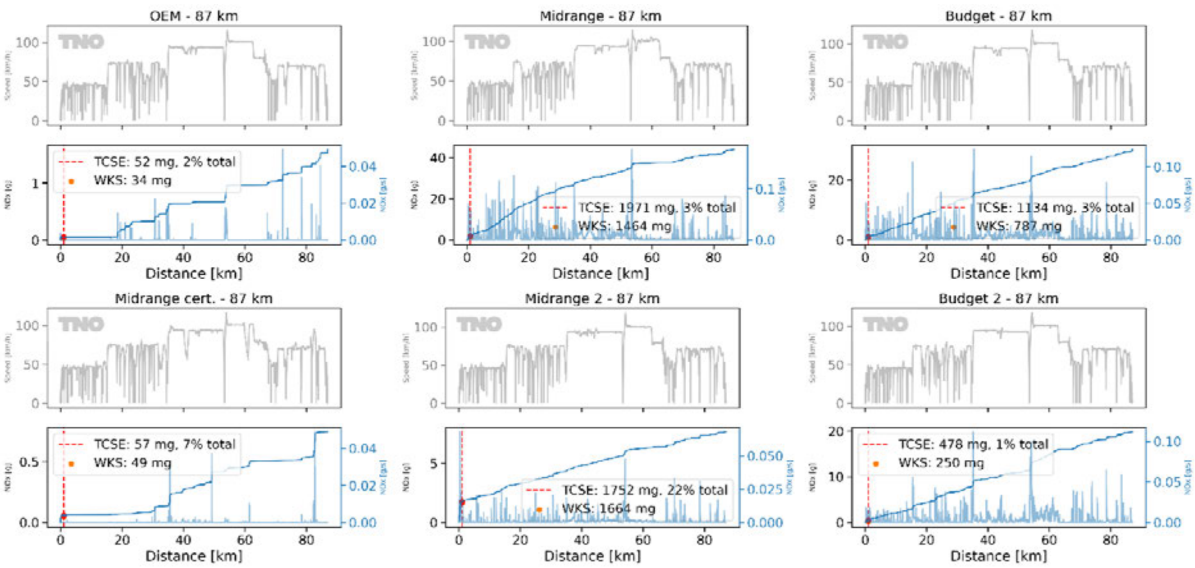

Figure A.1: Speed (top) and NO_x emissions (bottom) during the trips driven by the Toyota Prius, with each different catalyst configuration. The red dotted line at 1 km indicates where the cold start is considered complete: the total cold start emissions (TCSE) in the first kilometre are noted as a percentage of the total trip emissions. WKS (Wegtype Koude Start) is currently defined as the difference between the emissions in the first kilometre, and the average emissions of the entire trip, i.e. the cold start extra emissions. There is a clear difference in magnitude between the OEM and Midrange cert. and the other four configurations, though it should be noted that here differences in the use of the combustion engine are not considered (see Section A.1.1 for further discussion).

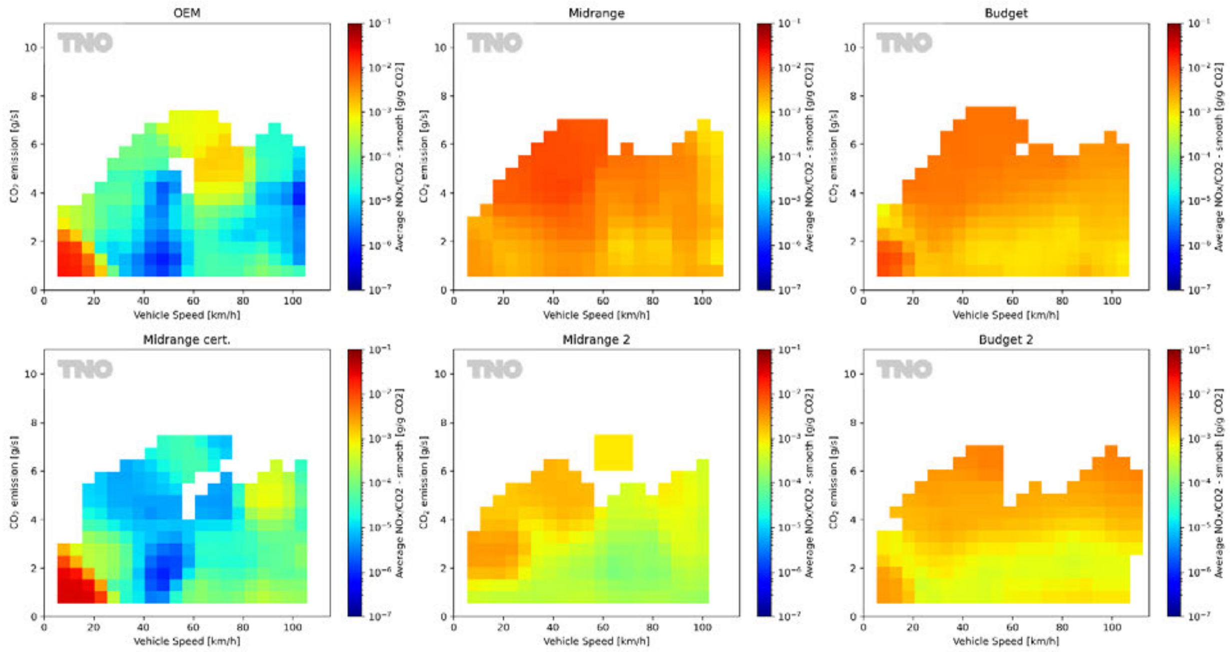

Figure A.2 : NO_x/CO_2 emission maps for the Toyota Prius per catalyst configuration, as a function of CO_2 and speed. The NO_x/CO_2 ratio normalises NOx levels with respect to the CO_2 emissions which can highlight local emission minima. For example, both the Budget catalysts have (slight) minima between 60 – 80 km/h demonstrating that there is a relative advantage in driving at these speeds. Comparatively, as noted when examining the NO_x maps, both the OEM and Midrange cert. have 'sweet spots' between 40 – 60 km/h where the emissions are several orders of magnitude lower than those at speeds less than 20 km/h. The OEM catalyst also has an additional local minimum at higher speeds and CO_2 emissions between 2 – 5 g/s, demonstrating its efficacy at higher speeds, i.e. situations relevant on the motorway.

A.1.1 Behaviour maps can be used to normalise the driving behaviour of hybrid vehicles

One of the challenges of direct comparisons between trips of hybrid vehicles is the usage of the combustion engine. Due to a range of parameters, including driver inputs and the battery's state of charge, the combustion engine in a hybrid vehicle can be used a lot less consistently across similar on-road trips compared to a non-hybrid vehicle. This can lead to differing fuel consumptions over the trip, but it also means different areas of the emission map (AEM) are covered during the trip: if the electromotor is on, the CO_2 emissions at that moment are lower.

If different areas of the AEM are covered during a trip, substantially different emissions can occur even if the total fuel consumption is similar. For example, in the case of the OEM catalyst (Figure A.3), there are multiple orders of magnitude between the emissions at 5 g/s CO_2 at 50 km/h, compared to 5 g/s CO_2 at 100 km/h. For this reason, behaviour maps (BM) can be used to normalise the behaviour across the trips, and ensure that the different areas of the emission maps are consistently covered.

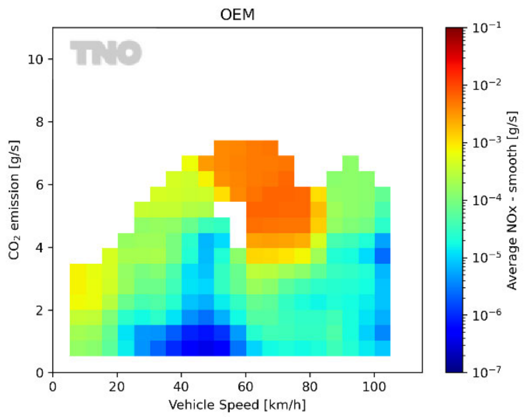

Figure A.3: Emission map of the NO_x emissions as a function of CO_2 and speed, of the Toyota Prius with the original OEM catalyst, as reproduced from Figure 3.2. Red indicates higher NO_x emissions; the localisation of these higher emissions demonstrates differences in catalytic function

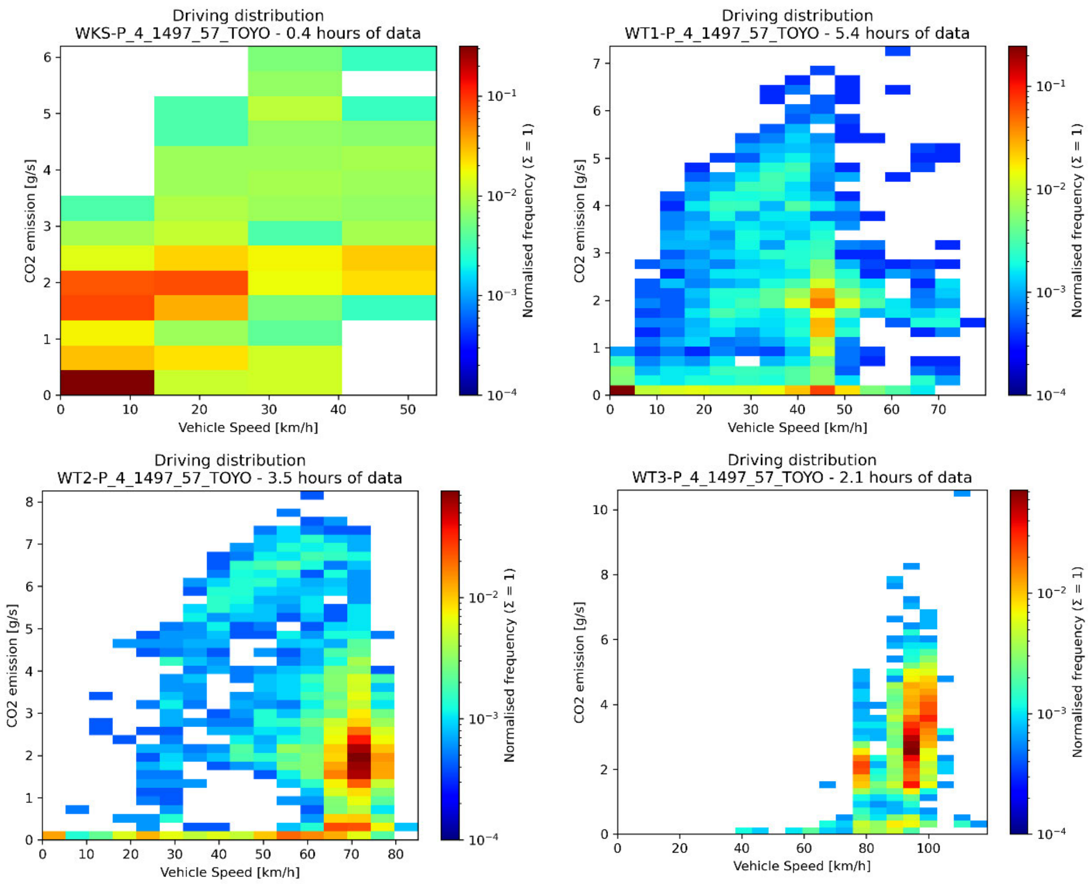

Figure A.4: Normalised frequency of CO_2 emissions and vehicle speed, where dark red indicates the area which occurs most often for the four road types now included in VERSIT+: WKS (cold start extra emissions in the first kilometre), WT1 (urban), WT2 (rural) and WT3 (motorway).

The BMs are made using all the trips driven by the Prius, including all the catalyst configurations, so that each map contains all the driving on that road type (Figure A.4). The relative frequency of a certain speed and CO_2 bin as determined in the BM is then used to weigh that respective bin in the relevant AEM to give one emission factor per road type per catalyst configuration that has been normalised for combustion engine usage.
The weighing makes use of earlier developed methodology to combine AEMs to account for data availability [10].

A.2 Three modified vehicles

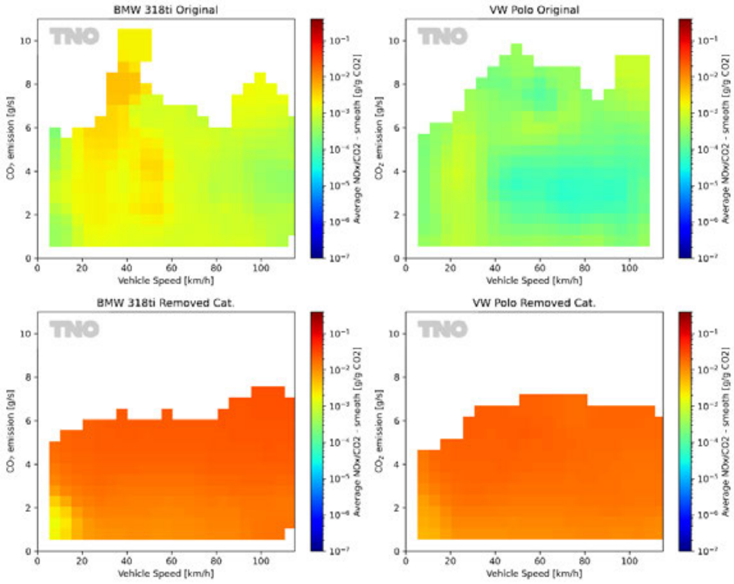

Figure A.5: NO_x/CO_2 emission maps for the three modified vehicles, as a function of CO_2 and speed. The NO_x/CO_2 ratio normalises NOx levels with respect to the CO_2 emissions which can highlight local emission minima. As would be expected, the vehicles with a removed catalyst show consistently high emissions. As mentioned earlier, the Renault Twingo shows local minima at low CO_2.

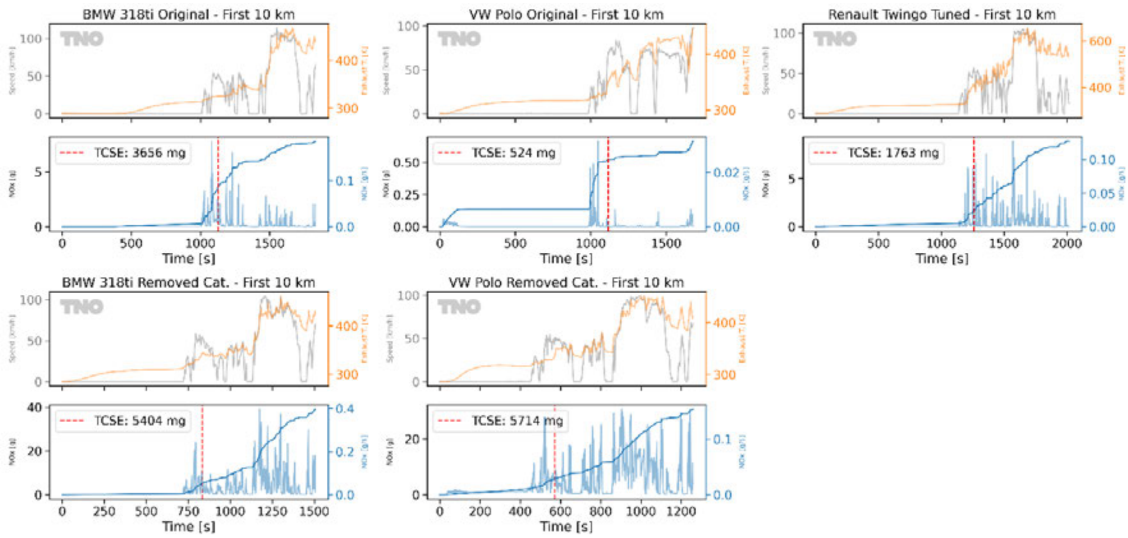

Figure A.6: Speed and exhaust gas temperature EGT (top, grey and orange respectively) and NO_x emissions (bottom) during the first 10 kilometres of the trips driven by the three modified vehicles. The red dotted line indicates when 1 km has been driven; the total cold start emissions (TCSE) in the first kilometre are noted. The trips are started with a period of idling, during which the ECT plateaus. The difference between the original and removed catalyst states are further emphasised when looking at the emissions as a function of time. Especially the VW Polo demonstrates the efficacy of the catalytic converter after the cold start.

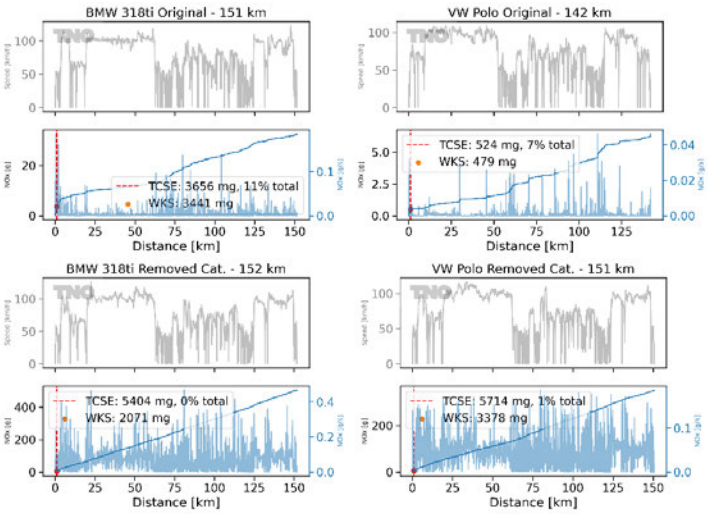

Figure A.7: Speed (top) and NO_x emissions (bottom) during the trips driven by the three modified vehicles. The red dotted line at 1 km indicates where the cold start is considered complete: the total cold start emissions (TCSE) in the first kilometre are noted as a percentage of the total trip emissions. WKS (Wegtype Koude Start) is currently defined as the difference between the emissions in the first kilometre, and the average emissions of the entire trip, i.e. the cold start extra emissions.

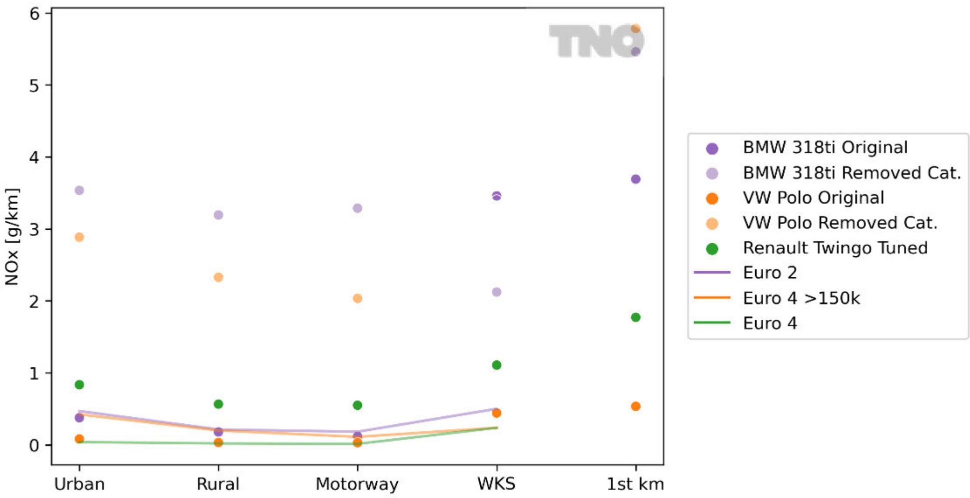

Figure A.8: NO_x emissions per road type for the three modified vehicles (dots) as compared to the relevant VERSIT+ emission factors (lines). The emissions during the first kilometre (1st km) are also shown. The urban, rural and motorway emissions for the BMW and VW are in line or lower than the current emission factors, though the BMW cold start is substantially higher. Of note is that the tuned Renault Twingo is significantly higher than the expected emissions for a Euro 4 vehicle with mileages lower than 150 000 km: in urban areas this leads to an extra 800 mg/km NO_x.

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