Anna van Buerenplein 1
2595 DA Den Haag
P.O. Box 96800
2509 JE The Hague
The Netherlands

www.tno.nl

T +31 88 866 00 00

TNO report

TNO 2019 R10541v2

Effects of a software update on NO_x emissions and performance of a VW Polo

Date	29 November 2019
Author(s)	A.P. Indrajuana R.N. van Gijlswijk N.E. Ligterink R.T.M. Smokers P.R. Balakrishnan
Copy no	2019-STL-RAP-100320802v2
Number of pages	42
Sponsor	Ministry of Infrastructure and Water Management
Project name	MaVe
Project number	060.31972

Samenvatting

Inleiding

Volkswagen heeft de software van enkele typen Euro 5 voertuigen bijgewerkt, met het doel om een illegale zogenaamde defeat device te verwijderen. In de media werden in 2018 zorgen geuit over mogelijke negatieve effecten van deze software-update op prestaties, brandstofverbruik en onderhoud van de betreffende voertuigen. Om antwoord te kunnen geven op vragen hierover uit de Tweede Kamer[1], heeft het Ministerie van Infrastructuur en Waterstaat TNO gevraagd het effect van de software-update te evalueren aan een voertuig dat door TNO in de praktijk gemonitord werd.

TNO heeft op het betreffende voertuig, een Euro 5 VW Polo 1.2TDI, een NO_x-monitoringssysteem geïnstalleerd, waarmee zowel voor als na de software-update informatie is verzameld over emissies, gebruik en prestaties van het voertuig.

Het gedrag van de VW Polo is onderzocht onder normale dagelijkse omstandigheden gedurende een periode van twee jaar, op het gebied van:

- De uitstoot van NO_x uit de uitlaat;
- brandstofverbruik en CO_2-emissie;
- motorvermogen en -koppel.

Kanttekeningen

- De monitoring is uitgevoerd op een enkel voertuig. Specifieke effecten, die samenhangen met de toestand van het voertuig of de manier waarop de software-update op dit voertuig is uitgevoerd, kunnen niet worden uitgesloten. Alleen onder de aanname dat het voertuig correct functioneert en dat de software-update correct is uitgevoerd, mogen de resultaten worden beschouwd als indicatie voor vergelijkbaar gedrag van andere voertuigen van hetzelfde model.
- Het is niet onderzocht of de NO_x-emissies lager zijn onder omstandigheden die dichter bij de NEDC-typekeurtest liggen. Dit kan dus niet worden afgeleid uit dit rapport. Ook is er geen onderzoek gedaan naar het eventuele effect van de software-update op hoe NO_x-emissies worden beïnvloed door variaties in testomstandigheden ten opzichte van de typekeuringstest. Onderzoek naar de mogelijke aanwezigheid en werkingsprincipes van 'defeat devices' is in de eerste plaats de verantwoordelijkheid van de typekeurende instanties, en de *technical services* in opdracht van typekeuringsautoriteiten.

[1] Zie antwoord van Staatssecretaris Van Veldhoven-van der Meer (Infrastructuur en Waterstaat), mede namens de Minister van Infrastructuur en Waterstaat (ontvangen 9 april 2018) op vragen van het lid Van Eijs (D66) over het bericht *«De Volkswagens zijn nog altijd veel te vies»* (ingezonden 21 februari 2018), ah-tk-20172018-1690

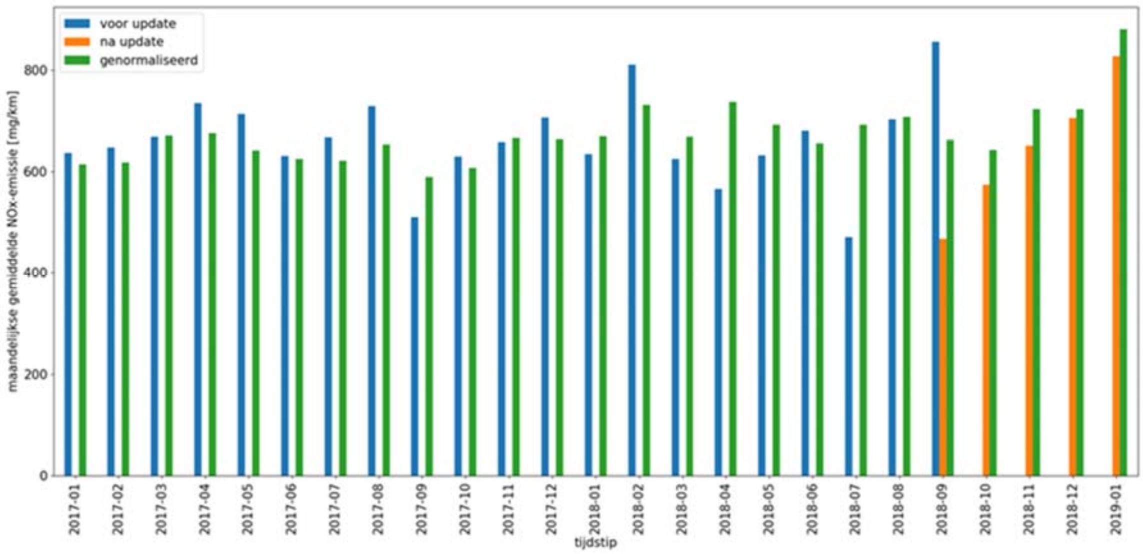
Methodiek
Emissies en inzet van de VW Polo zijn gemonitord tijdens dagelijks gebruik met het door TNO ontwikkelde SEMS-systeem[2] gebaseerd op sensor data.
De sensoren zijn werkzaam na ongeveer 100 secondes na start van de motor. Mogelijke veranderingen in de tijd vlak na de start zijn niet meegenomen.
Een belangrijk voordeel van het monitoren van emissies onder normale gebruiksomstandigheden in dagelijks gebruik is, dat effecten van eventuele herkenning door het voertuig van voor de typekeuring kenmerkende testomstandigheden worden uitgesloten. Een belangrijk nadeel van monitoren in de praktijk is dat variaties in de inzet, gekenmerkt door bijvoorbeeld gebruikspatronen, rijstijl en weer- en verkeersomstandigheden, leiden tot variaties in emissies. Verschillen in de gemiddelde inzet voor en na de software-update kunnen dus leiden tot een verschil in NO_x-emissies dat niet moet worden toegerekend aan de software-update. Om het effect van de software-update beter te isoleren en zichtbaar te maken is de data genormaliseerd voor uit de data afgeleide effecten van variaties in inzet.

De analyseresultaten zijn stap voor stap beschreven en integraal opgenomen in dit rapport, om de lezer in staat te stellen conclusies te controleren aan de hand van de analyseresultaten.

Conclusies
Uit de analyse kunnen de volgende conclusies getrokken worden met betrekking tot de invloed van de software-update op de emissies en prestaties van de gemonitorde VW Polo:

- De praktijkemissies van NO_x zijn zowel voor als na de software-update ongeveer 3,5 keer de norm van 180 mg/km die voor Euro 5 dieselpersonenvoertuigen geldt op de typekeuringstest. Deze NO_x-emissies komen zeer goed overeen met waarden die in 2012 zijn gemeten aan een andere Euro 5 VW Polo met dezelfde motor, en zijn vergelijkbaar met de praktijkemissies die in de periode 2010-2012 zijn gemeten aan een bredere groep Euro 5 dieselvoertuigen van verschillende merken en modellen[3].
- De software-update heeft geen merkbaar effect gehad op de gemiddelde NO_x-uitstoot van het voertuig. De variaties in emissies, die rondom de software-update optreden, kunnen worden toegeschreven aan bij de monitoring waargenomen variaties in voertuiginzet en gebruikscondities (zie figuur: de groene balkjes geven de emissies aan na correctie voor variaties in inzet en rijomstandigheden).

[2] Smart Emissions Measurement System, zie: https://www.tno.nl/sems
[3] Zie: TNO 2016 R10083 - NO_x emissions of Euro 5 and Euro 6 diesel passenger cars – test results in the lab and on the road



- In beperkte gebieden aan de rand van het emissiediagram (emissies als functie van de gereden snelheid en de CO_2-emissie, een maat voor vermogen) kan een kleine verandering in de specifieke NO_x-emissies worden waargenomen. In sommige gebieden is een toename zichtbaar, in andere een afname. In beide gevallen ligt de verandering tussen de 20 en 40%. In het deel van het emissiediagram, waar de motor voornamelijk wordt gebruikt, zijn de specifieke NO_x-emissies vrijwel gelijk gebleven.
- Over het geheel is er geen significante invloed van de software-update geconstateerd op het brandstofverbruik en de daarmee samenhangende CO_2-emissies. Er is een kleine afname van het brandstofverbruik gevonden bij hogere snelheden, tussen 100 en 130 km/uur, hetgeen samenviel met hogere NO_x-emissies.
- De monitoring van de CO_2-emissies per omwenteling van de motor geeft aan dat het maximale vermogen en koppel niet veranderd lijkt te zijn door de software-update.
- De monitoring van het zuurstofgehalte van het uitlaatgas geeft aan dat deze niet veranderd is door de software-update. Dit is een aanwijzing dat het gebruik van uitlaatgasrecirculatie (EGR) niet is veranderd. Meer gebruik van EGR hangt samen met een hogere NO_x reductie. Door gelijke NO_x uitstoot en de gelijke zuurstofconcentraties, die beide indicatief zijn voor een gelijke EGR-regeling, is de verwachting dat de software-update niet leidt tot een grotere onderhoudsbehoefte ten gevolge van het gebruik van uitlaatgasrecirculatie.
- De frequentie en de duur van roetfilterregeneraties is voor en na de update gelijk. Hieruit kan worden afgeleid dat de update geen invloed heeft op de roetuitstoot. Een verandering in roetemissies zou kunnen zijn veroorzaakt door een verandering in het gebruik van uitlaatgasrecirculatie. Dit is een indicatie dat de software-update niet leidt tot extra onderhoud, noch voor het roetfilter, noch voor de uitlaatgasrecirculatieklep.

Ruim vóór de software-update is uitgevoerd is een korte periode een stijgende trend waargenomen in de NO_x-emissies, die niet kon worden verklaard door de bekende invloed van het gebruik van het voertuig en de buitenluchttemperatuur. De emissies keerden terug naar het normale niveau na een onderhoudsbeurt waarbij 3 defecte injectoren zijn vervangen.

Deutsche Umwelthilfe testresultaten
In aanvulling op de analyse van de emissie monitoring van een Euro 5 VW Polo zijn ook testresultaten van vijf voertuigen van voor en na de software-update geanalyseerd. Deze testdata is afkomstig van de Deutsche Umwelthilfe en laten gemengde resultaten zien. De software-update heeft geen duidelijk positief effect. Er is vooral veel spreiding in de resultaten en de spreiding kan niet verklaard worden door de verschillen en uitvoering van de testen en de omstandigheden tijdens de twee testperiodes voor elke auto. Dit komt voornamelijk doordat de afhankelijkheid van de NO_x-emissies van omstandigheden, zoals de omgevingstemperatuur, niet uit de meetgegevens kon worden bepaald vanwege een beperkte datahoeveelheid.

Discussie
Het belangrijkste inzicht van deze studie is dat de emissies van voertuigen gedurende meerdere jaren gemonitord kunnen worden. De gegevens die daarbij verkregen worden maken het mogelijk conclusies te trekken over kleine verschillen in emissies. Met een testprogramma van enkele meetdagen is het niet mogelijk gegevens te verzamelen die met elkaar te vergelijken zijn. Het effect van regulier onderhoud komt alleen in langdurige monitoring naar voren. In het kader van toekomstige wetgeving, “post Euro-6/VI”, met de wens om de emissies over de volle levensduur van het voertuig onder controle te houden, is een verschuiving van testen naar gevalideerde monitoring wenselijk en mogelijk.

Summary

Introduction
Volkswagen has updated the software of some of their Euro 5 vehicles, for the purpose of removing an illegal defeat device. In the media concerns were expressed regarding possible negative impacts of this software update on performance, fuel consumption and maintenance of the affected vehicles. To address questions raised on this issue in Dutch Parliament, the Ministry of Infrastructure and Water Management has asked TNO to evaluate the impacts of the software update on a vehicle monitored by TNO in real-world operation.

TNO has had a NO_x monitoring system installed in a VW Polo 1.2TDI, that was used to collect data on emissions, vehicle use and performance both before and after the software update.

The behaviour of the vehicle has been investigated
under normal day-to-day use conditions over a period of two years, in terms of:

- NOx emissions from the tailpipe;
- fuel consumption and CO_2 emission;
- engine power and torque.

Caveats

- The monitoring is carried out on a single vehicle. Singular effects can therefore not be excluded. Assuming proper functioning of the vehicle and that the software update has been implemented correctly, however, the test results should be indicative of similar behaviour in other vehicles of the same model.
- Whether NO_x emissions are lower in conditions close to the NEDC type-approval test compared to normal use conditions, has not been investigated, and cannot be concluded from this work. Also, possible impacts of the software update on how NO_x emissions are influenced by deviations in test circumstances relative to the type approval test have not been investigated. Investigations into the possible presence and working principles of defeat devices are foremost the responsibility of type-approval authorities, and technical services working on their behalf.
- During the first period after the start of the engine, in the order of 100 seconds, the NO_x sensor is not ready for operation, because the sensor must be heated first. Changes in emission behaviour in this period due to the software update are not analysed, due to the lack of data.

Methodology
Emissions and use of the VW Polo have been monitored during daily use with the sensor-based SEMS[4] system developed by TNO. The sensors are active after about 100 seconds after starting the engine. Possible changes just after the start of the vehicle are not taken into account.

An important advantage of monitoring emissions under normal conditions of daily use is that the effects of any recognition by the vehicle of test conditions characteristic of the type approval are excluded.

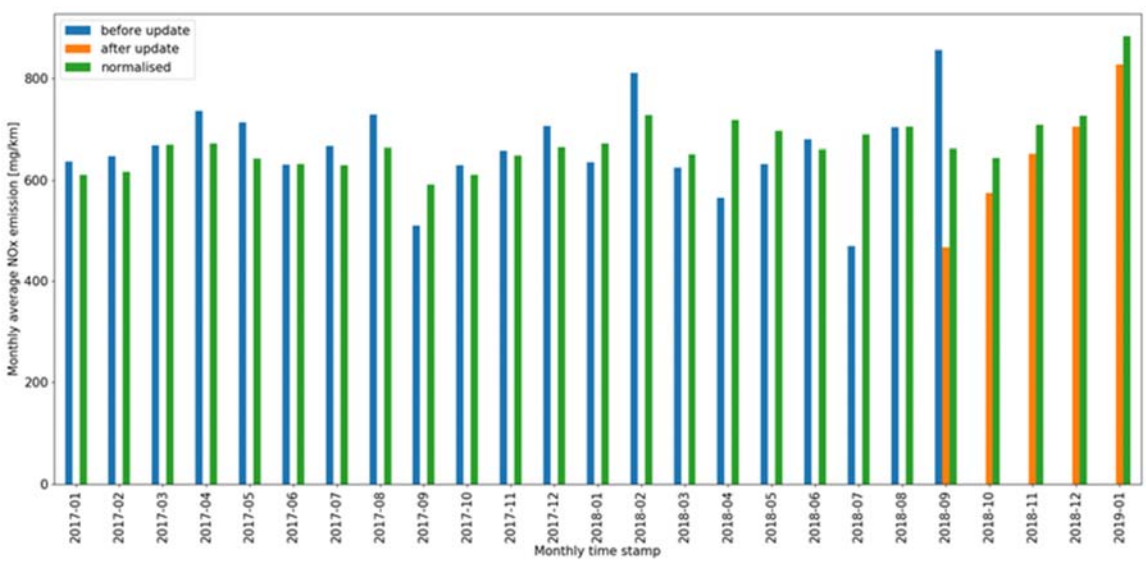
[4] Smart Emissions Measurement System, zie: https://www.tno.nl/sems

An important challenge with real-world monitoring variations in the use of the vehicle, characterised by e.g. use patterns, driving style and weather and traffic circumstances, lead to variations in emission. Differences in the average use of the vehicle before and after the software update can therefore lead to a difference in NO_x emissions that should not be attributed to the software update. To better isolate and visualize impacts of the software update the monitoring data has been normalised for effects of variations in use that have been derived from the monitoring data.

The analysis results are presented step by step and in their entirety, to allow readers to draw their own conclusions.

Conclusions
From the analysis the following conclusions can be drawn for the impact of the software update on the emissions and performance of the monitored VW Polo:

- Both before and after the update the real-world NO_x emissions are around 3.5 times the 180 mg/km emission limit applicable on the type approval test for Euro 5 diesel vehicles. These NO_x emissions are in agreement with values measured on a different Euro 5 VW Polo with the same engine in 2012 and are comparable to real-world emissions measured in the period 2010-2012 on a wider range of Euro 5 diesel vehicles of different makes and models[5].
- The software update has had no appreciable impact on the average NO_x emissions of the vehicle. The variations in emissions, that occur around the software update, can be attributed to variations in vehicle use and use conditions (see figure: the green bars show the average emissions after correction for variations in vehicle use and use conditions).



- In limited areas on the edges of the emission map (emission plotted as function of vehicle speed and CO_2 emission rate as a proxy for power) some change in specific NO_x emissions can be observed.

[5] See: TNO 2016 R10083 - NO_x emissions of Euro 5 and Euro 6 diesel passenger cars – test results in the lab and on the road

In some areas an increase is observed while in other areas emissions decrease. In both cases the changes are in the range of 20% to 40%. In the part of the emission map where the engine is mostly operated, specific NO_x emissions remained practically the same.
- Overall the software update is found to have a negligible impact on fuel consumption and associated CO_2 emissions. Only a small decrease in fuel consumption is observed at higher speeds, of 100 km/h to 130 km/h, together with increased NO_x emissions.
- The monitoring of the CO_2 emissions per engine rotation provide an indication that the maximum power and torque are not affected by the software update.
- The monitoring of the oxygen content of the exhaust gas shows no change. This indicates that the use of the exhaust gas recirculation (EGR) is likely not affected by the software update. In combination with the same level of NO_x emissions before and after the update, also signalling the same EGR level, indicate that the software update is not expected to lead to increased maintenance associated with the EGR.
- The frequency and duration of DPF regenerations is the same before and after the software update. This indicates that the update does not affect engine out emissions of soot. A change in soot emissions could be caused by changes in EGR operation. This is a further indication that the software update does not lead to increased maintenance, in this case associated with both the DPF and the EGR.

Before the software update, during one interval of the monitoring period an increasing trend was observed in the NO_x emissions which could not be explained by the known influence of vehicle usage and ambient temperature. Emission levels turned back to normal after a service event in which 3 defective injectors were replaced.

Deutsche Umwelthilfe test results
In addition to the analysis of the emission monitoring of a Euro 5 VW Polo, results from the Deutsche Umwelthilfe of five vehicles tested before and after the software update were analysed. The test data show mixed results with the software update having no clear positive effect. There is a lot of variation in the results and the spread cannot be explained by the differences in the tests and the conditions during the two test periods for each car. This is mainly because the dependency of the NOx emissions on test conditions, such as ambient temperature, could not be determined from the measurement data because of a limited amount of data.

Discussion
Above all, this study has shown that it is possible to perform emission monitoring of vehicles over multiple years. Furthermore, it is possible to collect sufficient statistics to draw conclusions from this data, which extends beyond the conclusions that can be drawn from a multi-day test program. In particular the effect of maintenance has been shown in long-term monitoring. For future vehicle emission legislation, currently discussed under “post Euro-6/VI”, with the desire to control emissions over the entire life cycle of the vehicle, a shift from testing to validated monitoring is desirable and possible.

Contents

1 Introduction

Owners of Volkswagen vehicles in the Netherlands affected by the diesel-gate scandal have received requests to have their vehicles' software updated.
This update, intended to remove an illegal defeat device, is not compulsory for vehicle owners in the Netherlands and there has been some hesitation to have the update carried out, due to stories of increasing maintenance issues and reduced performance. TNO has had a NO_x monitoring system, SEMS[6], installed in a VW Polo since early 2017. This vehicle was equipped with the software eligible for an update. In September 2018 the vehicle was presented to a VW dealer for the software update. Upon request of the Ministry of Infrastructure and Water Management in the Netherlands, TNO has evaluated the effect of the software update, to address questions raised in Parliament.

In this study, the behaviour of the vehicle has been investigated under normal day-to-day use conditions over a period of two years, in terms of:
- NO_x emissions from the tailpipe;
- fuel consumption and CO_2 emission;
- engine power and torque of the engine.

This study concerns the effects in normal use of the VW software update. Whether NO_x emissions are lower in conditions close to the NEDC type-approval test compared to normal use conditions, was not investigated. Investigations into the possible presence and working principles of defeat devices are foremost the responsibility of the type-approval authorities. Instead, this study investigated the consequences of the applied software update for real-world emissions, fuel consumption, and performance from a societal and car owner perspective. Problems with maintenance, higher fuel consumption, and lower engine power have been put forward as issues with the software update, from the experiences of vehicle owners. These questions have been included in this investigation.

The complexity of the study is in the fact that the measurement data was collected in normal use. Tests before and after the update, under controlled conditions, like type-approval tests, were not performed. Hence, conditions, situations, use patterns, and driving style will vary over time. The data has been analysed in such a way, that the effect of these potential variations is cancelled out or normalized as much as possible, in order to isolate the effect of the software update. The analysis results are presented separately and entirely, to allow readers to draw their own conclusions.

The results present an indication of the effect of the software update on real-world emissions. This means that no conclusions can be drawn on a possible decrease of the NO_x emissions under conditions that are closer to the NEDC type-approval test. Furthermore, the analysis of a single vehicle is no conclusive proof for the effects of the VW software update in general. The effect on other vehicles equipped with the same engine, and vehicles equipped with different engines that are eligible for the software update, is unknown. Hopefully, the study provides indications on the different aspects related to the software update for real-world performance.

[6] Smart Emissions Measurement System, see: https://www.tno.nl/sems

Of this specific type-approval-variant-version combination of the VW Polo there were 6363 vehicles in the Netherlands on 1-1-2019. Moreover, the three-cylinder 1.2 litre diesel engine of Volkswagen is applied in many more vehicles. The effect in other vehicles is unknown, since different software updates may be applied.

1.1 Report structure and notes regarding version 2

After this introduction, chapter 2 covers the properties of the vehicle and the maintenance history. Following this, chapter 3 discusses the global emission results. Variations of the NO_x-emissions over time are analysed in chapter 4, followed by the investigation of effects of the update on fuel consumption, CO_2 and engine power (chapter 5). Maintenance related issues are documented in chapter 6. Chapter 7 contains additional results of testing performed by the Deutsche Umwelthilfe on similar vehicles. Finally, conclusions are drawn in chapter 8 and some discussion points are covered in chapter 9.

This document is a second version of the report numbered TNO 2019 R10541. This version of the report contains an additional chapter relative to version one. This includes the results of tests performed by the Deutsche Umwelthilfe on similar vehicles and is covered in chapter 7.

2 VW Polo use and maintenance

2.1 Technical data

From the ovi.rdw.nl the following information could be found regarding the vehicle on 1 February 2019:

Algemeen		
J	Voertuigcategorie	Personenauto (M1)
	Carrosserietype	Hatchback (AB)
	Inrichting	hatchback
D.1	Merk	VOLKSWAGEN
D.2	Type	6R
D.2	Variant	ABCFWA
D.2	Uitvoering	FM5FM52R031LLEVR67MG
R	Kleur	Wit
D.3	Handelsbenaming	POLO
K	Typegoedkeuringsnummer	e1*2001/116*0510*08
	Plaats chassisnummer	Rechts, rechter motorruimte
	Aantal eigenaren privé / zakelijk	2 / 0

Vervaldata en historie		
	Vervaldatum APK	25-05-2019
B	Datum eerste toelating	20-05-2011
I	Datum tenaamstelling	02-08-2013
	Tijdstip tenaamstelling	18:55
	Datum eerste afgifte Nederland	20-05-2011

Terugroepacties		
	Status terugroepactie(s)	Geen terugroepactie(s) geregistreerd

Motor		
P.1	Cilinderinhoud	1199 cm³
	Aantal cilinders	3
	Type gasinstallatie	Niet van toepassing
	Zuinigheidslabel	A

Milieuprestaties		
P.3	Brandstof	Diesel
	Brandstofverbruik stad	4.1 l/100km
	Brandstofverbruik buiten stad	3 l/100km
V.8	Brandstofverbruik gecombineerd	3.4 l/100km
U.1	Geluidsniveau stationair	73 dB(A)
U.2	Toerental geluidsniveau	3150 min-1
U.3	Geluidsniveau rijdend	Niet geregistreerd
P.2	Nettomaximumvermogen	55 kW
	Nominaal continu maximumvermogen	0 kW
V.5	Uitstoot deeltjes (licht)	0.0001 g/km
V.5	Uitstoot deeltjes (zwaar)	Niet geregistreerd
V.6	Roetuitstoot	0.5 m^{-1}
	Retrofit Roetfilter	Nee
	Milieuclassificatie	Euro 5
V.7	CO2 uitstoot gewogen	Niet geregistreerd
V.7	CO2 uitstoot gecombineerd	89 g/km
V.9	Milieuklasse EG Goedkeuring (licht)	715/2007*692/2008A
V.9	Milieuklasse EG Goedkeuring (zwaar)	Niet geregistreerd

2.2 Ownership and use

In the two years that the car was monitored, it has recorded driving data for almost 30,000 kilometres. The vehicle use had intermittent periods of limited operation. The vehicle was not used for regular, daily operations, such as commuting. Most of the distance was covered within the Netherlands, and a substantial part in Flemish Belgium. Hence the use was at limited altitude and velocity, given the speed limits in these regions.

Figure 2.1 shows the intensity of use of the vehicle over the monitoring period.

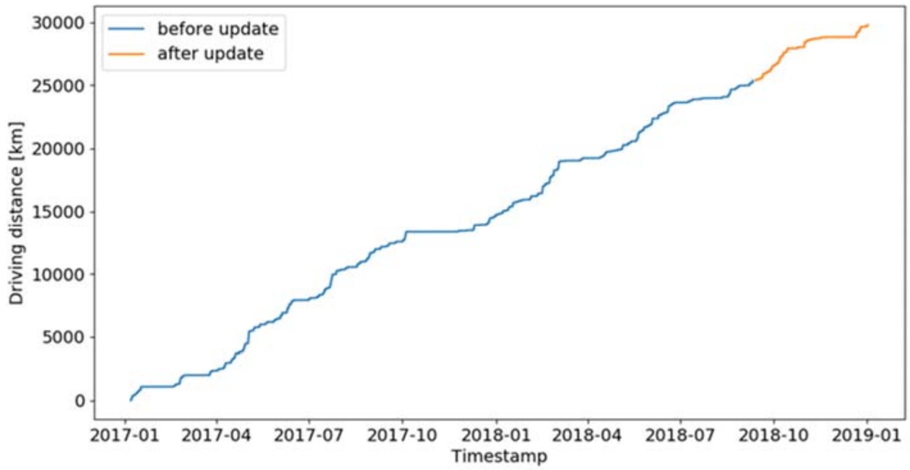


Figure 2.1: The distance against time shows a steady, yet variable use pattern over the two years of monitoring, with periods without usage of up to a month.

2.3 Maintenance history

The car was in regular maintenance, in accordance with the service interval plan of the manufacturer. An overview of the maintenance history is given in Table 2.3-1. No engine fault codes were identified before, during or after the monitoring period.

Table 2.3-1: Maintenance history of the tested vehicle

Date	**Maintenance**	**Mileage in km**	**Dealer**	**-**
13-9-2018	Software update	206.770	VW	Including certificate
6-3-2018	Small service	197.502	Bosch Service Center	According to service plan
2-2-2017	Large service	172.564	Bosch Service Center	According service plan, replacing all defective diesel injectors (3)
22-8-2016	Invitation to update software			Information that a new software update is available
19-5-2016	Small service	145.739	Bosch Service Center	According service plan
3-11-2015	Letter concerning fraud			Information that vehicle is affected
17-9-2015	Small service	121.246	VW	According service plan
4-5-2015	RDW Call back action	105.949	VW	TRA 2047 (risk of defect fuel filter housing), new housing
27-10-2014	Small service	90.000	VW	According to service plan
22-1-2014	Small service	59.516	VW	According to service plan
27-11-2012	Small service	30.259	VW	According to service plan
17-5-2011	First service	0	VW	According to service plan

TNO actions:

- 2 March 2018: SEMS NO_x-sensor replaced, data corrected accordingly;
- 17 April 2018: (faulty) SEMS NO_x-sensor replaced, data corrected accordingly;
- 6 January 2017: SEMS monitoring system installed.

2.4 Software versions

The software update has been carried out by a Volkswagen dealer on 13 September 2018. The software version before the update was 03P906021B 9707a. After the software update, the version number was 03P906021B 9980a.

3 Global results in emission maps

3.1 Approach

The SEMS equipment was installed on January 6, 2017 and has since then continuously measured NO_x concentrations in the tailpipe when the vehicle is in use. The system is currently still running (February 2019). Additional signals from SEMS sensors, such as exhaust gas temperature, became available in the course of 2017.
The data used in the analysis are:
- From SEMS sensors: NO_x concentration, O_2 concentration, exhaust gas temperature;
- From the GPS sensor: position, altitude, speed;
- From on board diagnostics of the vehicle (OBD): AAT (Ambient Air Temperature), MAF (Mass Airflow), RPM (engine speed), and ECT (Engine Coolant Temperature).

In total, data is available for about 400 hours of vehicle use.

Each of these data sources was logged at a 1 Hz rate: one observation per second. The NO_x concentration from the SEMS sensor was multiplied by the flow of gas in the exhaust, which was derived from the MAF signal and the O_2 concentration, resulting in a NO_x emission in grams per second. Combining this information with the distance driven, the NO_x emission in grams per kilometre was calculated.

The NO_x sensor requires about 100 seconds to heat up, after the start of the engine. Therefore, from the monitoring data, the first emissions after the start of the engine is missing. Therefore, specific changes in emissions over the monitoring period related to the engine start cannot be analysed. The dependence on the engine coolant temperature, for the second part of the engine heat up, is analysed.

There is a large variation in the instantaneous NO_x emission level, which correlates with many of the other signals logged. The NO_x emissions are most strongly correlated with the CO_2 emission rate, which is a proxy of the power delivered by the engine. With other signals there is a weaker correlation. In the following chapters the relationships are analysed and presented in more detail. Next, these derived relationships are used to normalise the NO_x emissions, to compensate the results for the variation in usage and driving conditions.

3.2 Average emission rates

The average NO_x emissions before and after the software update are 656 mg/km and 571 mg/km respectively. Based on these numbers one might conclude that the reduction of 13% in the average emissions can be attributed to the software update. However, as stated in the previous paragraph the instantaneous emission rate varies a lot and is influenced by a number of other conditions. In the next paragraphs it is investigated to which extent the differences can be explained by other conditions.

3.3 Normalized emission map

Plotting the average emissions as a function of velocity shows that the NO_x emissions vary considerably over the speed range. The lines in Figure 3.1 show a level of approximately 400 mg/km for the 50-100 km/h interval. In the higher and lower speed ranges the levels are, on average, more than a factor of two higher. Looking at the histogram bars in the same graph, minor differences before and after the software update can be observed with respect to the frequencies of occurrence of different velocities. Before the update, driving at 120 km/h and higher velocities occurred more frequently than after the update. This seems to be the main cause of the higher average NO_x emissions per kilometre before the update.

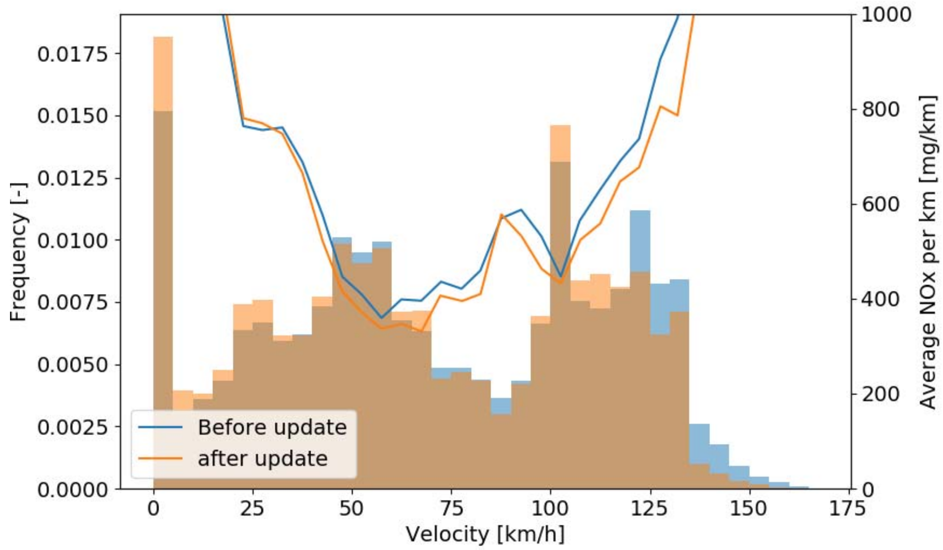


Figure 3.1: The average NO_x emission rates at different speeds (blue and orange lines) show similar results before and after the update. Before the update more high velocity (>=120 km/h) driving occurred, which comes with relatively high emissions of up to and above 1000 mg/km. This seems to be the main cause of the difference in the overall average NO_x emissions before and after the update.

The differentiation by velocity already gives a good indication that there is only a limited effect of the software update on NO_x emissions in normal use of this vehicle. One of the remaining potential factors of influence is driving dynamics.
For example, the fact that the emission levels at 100 km/h are lower than those at 90 or 110 km/h, is known to be (partially) caused by low driving dynamics at 100 km/h; it is a typical cruising velocity. The dynamics are reflected in the engine load, fuel rate, or CO_2 rate. Observed differences in emission at the same speed before and after the update may thus result from differences in the underlying distribution of engine loads.

A map of the NO_x emission as a function of CO_2 emission and speed, disaggregates the NO_x emission level for acceleration. This map was made for the data before and after the update. In Figure 3.2, the difference between these two maps is shown (after update minus before update). It averages the variation over time, also in each of the two periods. A blue colour shows a decreased NO_x emission rate (mg/s) at a particular speed/CO_2-rate combination, a red colour an increased emission rate.

The graph shows effects of about 2 mg/s or less, leading to variations of 100 mg/km at maximum. Note that the edges of the graph are seldomly reached in normal operations or are associated with low absolute emissions. This means that little impact can be associated with the differences seen on the edge of the graph.

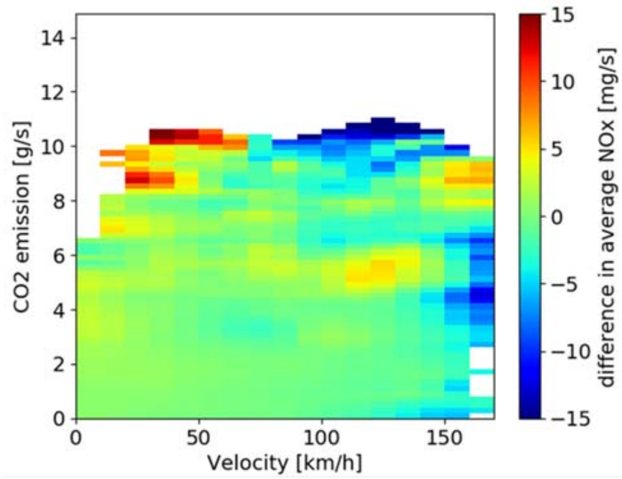


Figure 3.2: The change in NO_x emissions after the update, as a function of velocity and CO_2 rate, shows minor variations in the areas of normal operation. Most notably, at 120-130 km/h and 5 g/s CO_2 a minor increase in NO_x emissions can be observed.

Using a relative scale in Figure 3.3 instead of an absolute scale in mg/s, it can be confirmed that at the same velocity and engine load, the NO_x emissions in normal operation changed up to 20%. Only at the extreme borders, which are seldomly reached at the top, or associated with very low absolute emissions at the bottom, the effects can be larger. However, as explained, the results at these borders have a negligible effect on the average results.

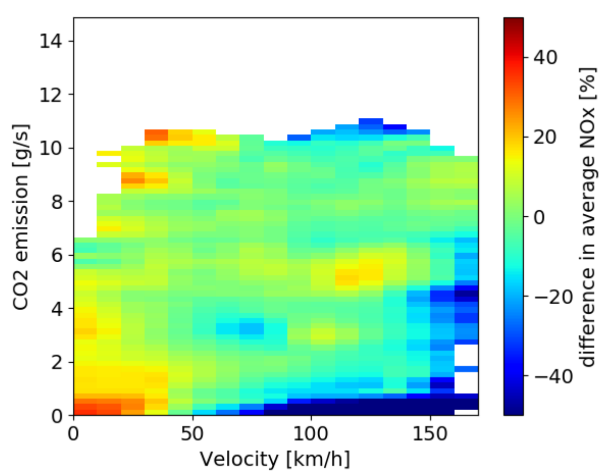


Figure 3.3: On a relative scale, the change in NO_x emissions between before and after the update shows effects typically lower than 20%. Only below 0.5 g CO_2/s larger relative effects are observed, but these are associated with very low absolute emissions.

The areas around 120 km/h and 5 g/s CO_2 rate and 75 km/h and 3 g/s CO_2 require special attention. It might have been the case that for the involved engine loads the change in NO_x emissions is linked to a change in engine efficiency and resulting CO_2 emissions[7]. This would limit the comparability of the results in Figure 3.2 and Figure 3.3. The comparability has been further investigated in Chapter 5, and it is found that the link between NO_x emissions and CO_2 emissions is not the cause for the effect in Figure 3.3.

3.4 NO_x emission control by EGR

The VW Polo Euro 5 has limited technical means to control NO_x emissions. The Exhaust Gas Recirculation (EGR) is the most important technology applied to this vehicle. With EGR the NO_x emissions are reduced due to a combination of a lower combustion temperature and a reduced oxygen concentration, which both reduce the formation of NO_x molecules. A difference in EGR operation before and after the update could also be visible in the oxygen concentration in the exhaust. In the case of no change in the exhaust gas decomposition, it is an indication that the EGR is at the same level. More EGR, in the same conditions causes a lower oxygen fraction and a lower exhaust mass flow. At a given power demand (indicated by the CO_2 rate), a lower amount of oxygen can be linked to a lower NO_x rate. This is visible in Figure 3.4: the colours wash towards yellow on the left-hand side of the graphs. For the same CO_2 emission and fuel consumption, average NO_x emissions vary typically by a factor of two or more with oxygen concentration.

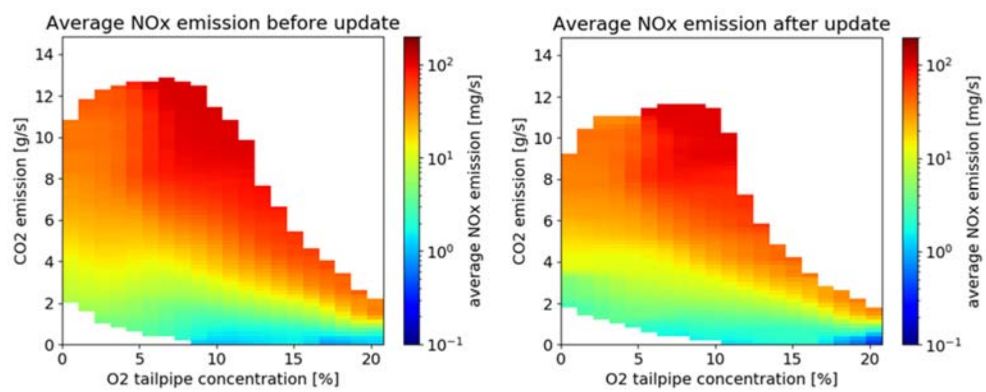


Figure 3.4: Lower power results in lower CO_2 and lower NO_x (vertical lines). But lower oxygen is also associated with lower NO_x (horizontal lines). The figure to the right shows that, after the update, the discernible differences in this result are small.

From the colour patterns in the two graphs, it can be observed that the update had limited or no effect on the NO_x emissions at a given power demand (CO_2 emission) and oxygen concentration. This means that, insofar the update resulted in changes other than EGR rate, these changes had no effect on the NO_x emissions.

[7] If the CO_2 emission at a specific condition has changed (e.g. constant speed, 75 km/h), data points for this condition now land on a slightly different location in the graph: slightly higher or lower than before. As there is a link between NO_x emission and CO_2 emission, this would influence the average emission level at the affected locations in the graph. However, further investigation of the comparability of the conditions in the two graphs has pointed out that the link between NO_x and CO_2 emission levels is not the cause for the changes observed (see Chapter 5).

To see whether the EGR strategy has changed during the update, the frequency of the range of oxygen concentrations before and after the update was plotted, see Figure 3.5.

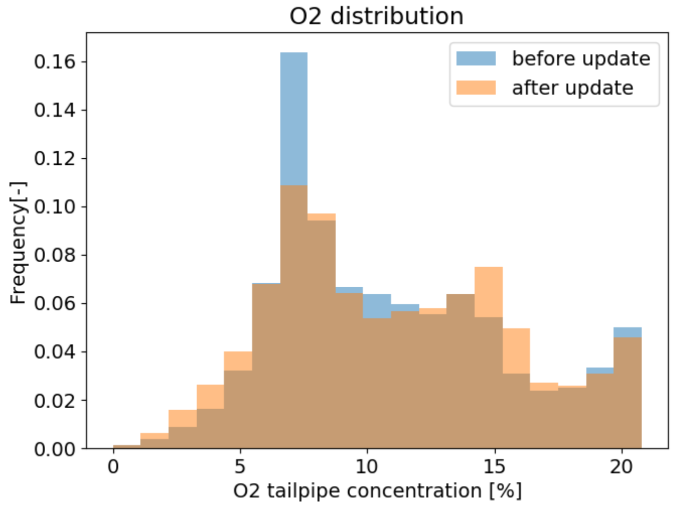


Figure 3.5: There is no shift in the distribution towards lower oxygen concentrations after the update. It is therefore unlikely that the EGR rate has increased after the update.

From this operational profile, no increase in the EGR use can be observed.
Note that a change in EGR use may affect the combustion process, leading to more soot, and specifically more persistent soot. This could affect the DPF (Diesel Particulate Filter) operation and may lead to maintenance issues. This secondary effect of EGR operation is investigated in Chapter 6.

4 Variations in emissions over time

As the vehicle was monitored in actual use, the use patterns and operating conditions before and after the software update were not identical. By normalising the NO_x emission data for variations in use and operating conditions, the changes in emissions not explained by these variations can be investigated. For example, changes in emissions due to a software update can be observed much better once the known other effects are compensated for. This is based on the assumption that the emissions are equal when the parameter values are equal. In order to perform the normalisation a formula was calculated for each parameter, that describes the relationship between the NO_x emission and this parameter. Together the formulae form a model that can predict the emissions. The difference between the prediction and the actual emissions at any given time shows the remaining variability in emissions that cannot be explained by the variation in model parameter values. An abrupt change in this difference can indicate, for example, an effect of the software update.

The formulae were derived from the entire data set, including driving data from before as well as after the update. This was done to have the best coverage of the range of values for each parameter, in other words: to have the best coverage for all operations and driving conditions. The effects before and after the update are therefore observed as relative effects with respect to the mean behaviour. Using all data for the model ensured differences in conditions, as included in the fit, are not wrongly construed as effects of the update, by extrapolating data from before the update to conditions after the update.

4.1 Averaging over time

The NO_x emissions can be predicted roughly by the vehicle velocity and the CO_2 rate from the exhaust. This forms the foundation of the emission prediction. Figure 4.1 shows a map of the average NO_x emission as a function of the combination of velocity and CO_2 rate. The map is based on all of the data collected. High power demand, indicated by high CO_2 rates, leads to high NO_x emissions. A secondary effect is the dependency on velocity. Note that the NO_x emission, indicated by the colour, has a logarithmic scale, with a factor 100 or more between low and high NO_x rates.

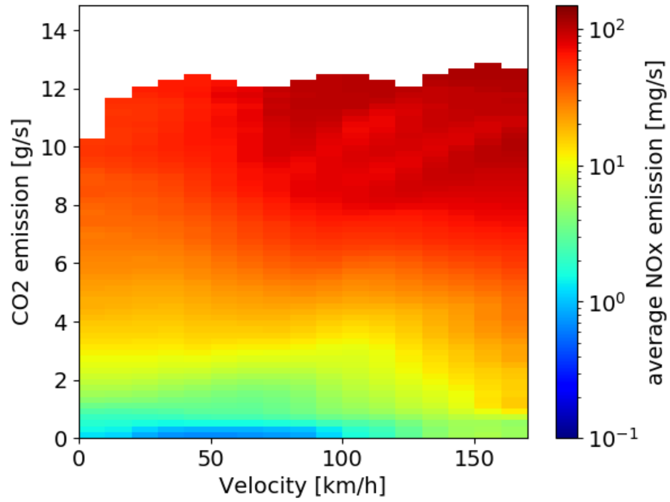


Figure 4.1: The average NO_x emissions for each velocity and CO_2 emission rate. From moderate to high power demand, the emissions increase more than tenfold.

As described in the introduction of this chapter, for each second, a prediction of the emission was made and compared to the measured value. To show the long-term effects, all the data is averaged over hourly periods, and the estimate and the measurements of the 400+ hours are plotted in the top part of Figure 4.2. The bottom part shows the difference between measurement and model (measurement minus model).

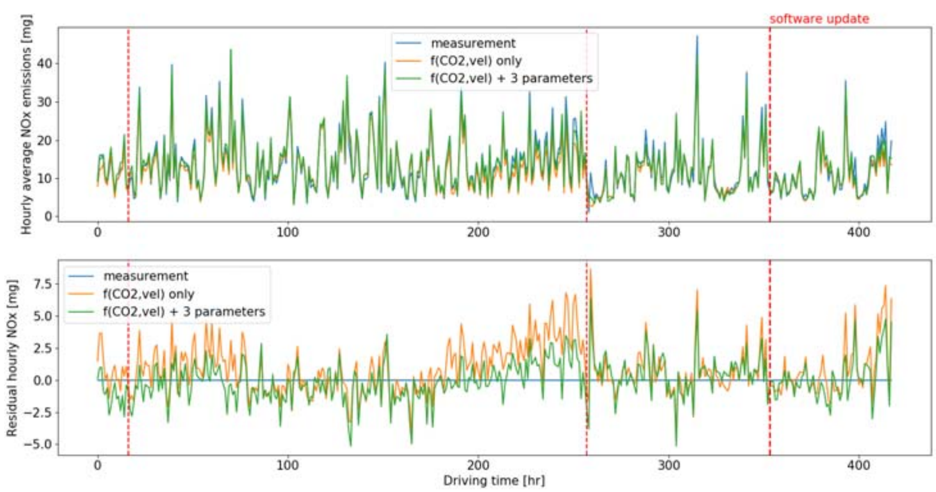


Figure 4.2 : The top figure shows the average NO_x emission over each hour: measured (blue), estimated on the basis of the emission map (orange), and the corrected estimate for effects of temperature, engine speed, and engine coolant temperature (green; see paragraph 4.2). The bottom picture shows the deviation of these estimates from the measurements. Dashed lines: maintenance events. The software update was applied at the last event, at 350 hours.

The deviations of the estimate are in the order of 10% of the total emissions. The additional parameters do reduce the deviation of the estimate over time. However, a residual effect remains.

The data after software update (dashed red line at 350 hours) does not show a systematic effect. The gradually increasing residue towards the 2nd line from the left at 270 hours, is analysed in paragraph 4.3.

4.2 Additional dependencies

In the emission estimates, based on the average emissions, not only the CO_2 rate and the velocity are important determinants. Also, other parameters affect the average emissions. This can be deduced from the correlation of the deviations between the estimated and the measured NO_x signals (orange line in the lower part of Figure 4.2) with these additional parameters. One by one the effects are determined and included in the model for the estimate.

Since the different parameters are correlated, the remaining effect attributed to a parameter added to the model depends on the parameters already incorporated in the estimate. The determined correlations are therefore not independent facts, but dependent on the procedure and order of decomposing the dependencies of the NO_x emissions.

The order of decomposition, used in the analysis presented here, is:

1. The map based on velocity and CO_2 rate.
2. Engine speed, which is strongly correlated with velocity.
3. Ambient temperature, which is a key feature in a number of defeat devices.
4. Engine Coolant Temperature, showing effects of cold start.

Figure 4.3 shows the relationship between the residual NOx emission and the first additional parameter analysed here: engine speed. The graph shows the average residual NO_x for each engine speed (dark red line) and the standard deviation (half transparent area around the line).

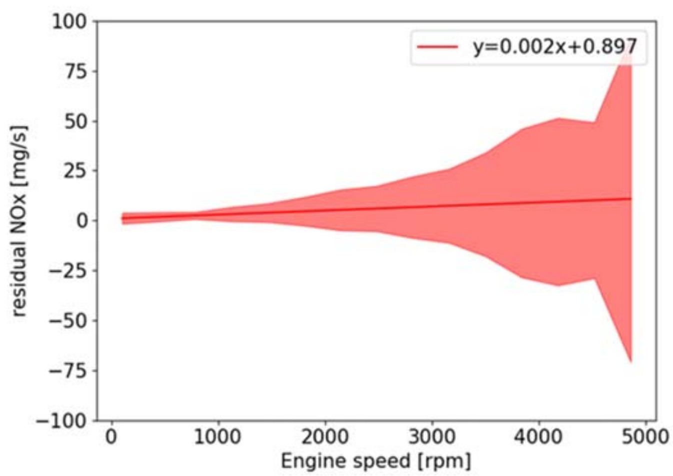


Figure 4.3: The residual NO_x emission in relation to engine speed: The difference between the measurements and the map-based estimate shows a small systematic correlation with engine speed. Over the whole range the change amounts about 4 mg/s. The data is plotted with blue points. Most data are centred around the zero axis; the standard deviation is given by the red area.

After applying the linear fit as presented by the formula in Figure 4.3, the remaining effects of engine speed are only minor. With higher engine speeds the residual emissions are slightly above zero. However, the uncertainty, and therefore the deviation of NO_x emissions for high engine speeds is large.

After the prediction is improved by including a factor for engine speed, the remaining effect of ambient temperature is rather small, as can be seen in Figure 4.4.

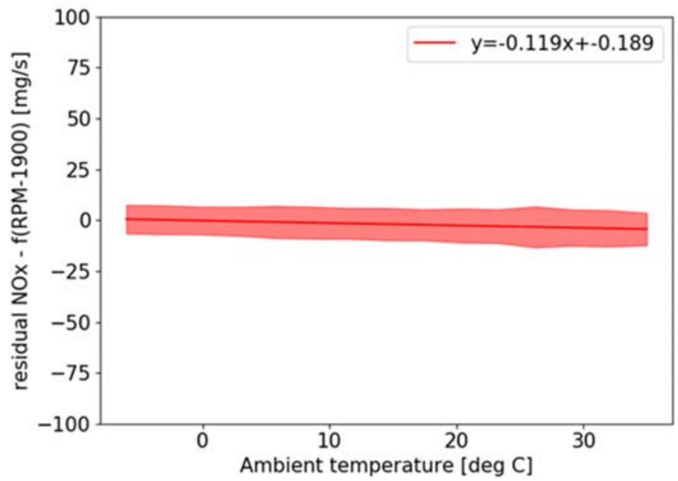


Figure 4.4: The residual NO_x emission in relation to ambient temperature shows a small effect of about 3 mg/s NO_x change over the whole temperature range.

The formula in Figure 4.4 shows that the remaining effect of ambient temperature is negative: higher temperatures on average lead to slightly lower emissions.

Now the prediction includes velocity, CO_2 rate, engine speed, and ambient temperature. Peeling off the dependencies like that, the correlation of the difference between the measurement and the prediction with the last parameter, the engine coolant temperature, is low. The engine coolant temperature is a proxy for the cold start. If the coolant temperature is low, the engine has typically just started. This can be associated with a different emission control strategy. The effect of the engine coolant temperature on the residual emissions is found to be very minor, however, as can be seen in Figure 4.5.

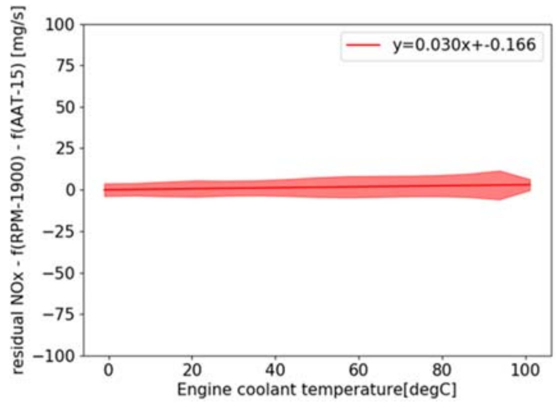


Figure 4.5: The residual NO_x emission (accounting for the map of engine speed and ambient temperature) shows a small correlation with coolant temperature. The effect is about 1 mg/s.

Together the parameters explain a large part of the residual emissions shown in Figure 4.2. Each of the different parameters can result in a few mg/s NO_x emissions on top of the emission map. The model for the prediction deviates typically less than 2 mg/s from the measured values. To investigate the remaining changes over time, the time series data is studied in the next sections.

4.3 Residual emissions

The major effect on top of the emission map estimates is the ambient temperature. The cold winter period of 2017-2018 does lead to an increase in emissions. Once compensated for this effect, there is still a gradual increase in the emissions over this period (hour 170 up to 250). The maintenance in March 2018, close to the end of the cold period, turns around the upward trend. See Figure 4.6.

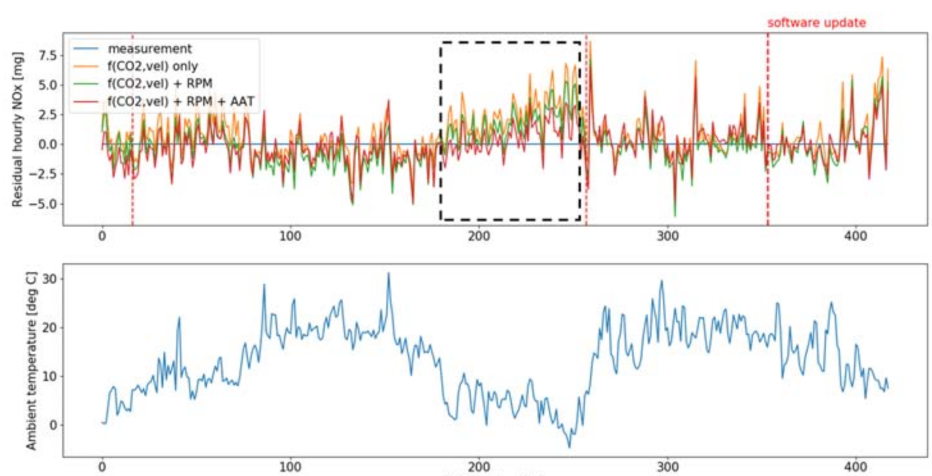


Figure 4.6: The hourly average of the deviations of the actual emissions from the predictions based on the average behaviour. The different lines include normalisation to different parameters. The red line includes AAT (Ambient Air Temperature) showing the largest effect. The bottom plot shows the temperature, with the cold winter period 2017-2018.

The maintenance of March 2018, the second dashed red line, at 250 hours, coincides with the end of the cold period. The other cold period, at the beginning of the time series, does not coincide with higher than average emissions, which seems to indicate that it was indeed the service in March 2018 that brought down the upward trend in NO_x emissions.

The rightmost red dashed line at 350 hours is the software update. The emissions hardly change. One could deduce a maximum effect of 1 mg/s from the Figure 4.6 across this red line. Given the average of 600 mg/km for this vehicle, that would yield an effect of 10% or less. Other variations with respect to the average emissions are larger. In particular, the regular maintenance at service intervals seems to reduce emissions more significantly.

4.4 Normalized monthly emissions

Plotting the monthly average emissions reveals a variation between 400 mg/km and 800 mg/km in the measurements. However, when corrected for the effects of variations in usage pattern and conditions, the remaining variation in emissions is smaller. Using the average vehicle and conditions use over the two years and adding the unexplained variations to that average emissions with the average use (green bars in Figure 4.7), the variation between months is less than 50 mg/km. No abrupt change in the remaining month-by-month variation can be observed at the software update. Right after the software update the normalised average monthly emissions show a small drop of a few percent, but this effect is negligible compared to the month-by-month variation. See Figure 4.7.

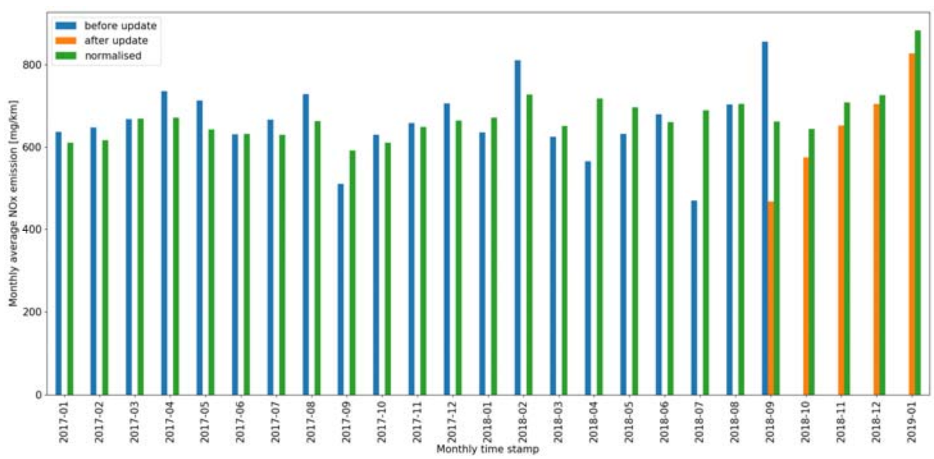


Figure 4.7: The monthly average measured emissions, in blue before the update, and orange after the update, and the normalised emissions, corrected for variations in use and conditions in green.

Both before and after the update the real-world NO_x emissions are found to be around 3.5 times the 180 mg/km emission limit applicable on the type approval test for Euro 5 diesel vehicles. These NO_x emissions are in agreement with values measured on a different Euro 5 VW Polo with the same engine in 2012 and are comparable to real-world emissions measured in the period 2010-2012 on a wider range of Euro 5 diesel vehicles of different makes and models[8].

[8] See: TNO 2016 R10083 - NO_x emissions of Euro 5 and Euro 6 diesel passenger cars – test results in the lab and on the road

5 Effects on fuel consumption, CO_2 and power

It is conceivable that the software update, applied to reduce NO_x emissions, has an effect on the real-world fuel consumption as well. Also, it is possible that the available amount of power has changed in parts of the engine speed range. Further analysis was done to see if any of these potential effects could be observed.

5.1 Fuelling data, fuel meter

The fuel meter of this vehicle is found to compare well with the fuelling data. Within the variations in vehicle use, there are no obvious effects observed of the software update on fuel consumption.

5.2 CO_2 emissions

The fuel consumption and CO_2 emissions are directly related for a given fuel. Isolating an influence of the update on fuel consumption is therefore possible as well by monitoring the CO_2 emission levels over the speed profile. It is necessary though to compensate for ambient temperature differences, because these have a noticeable effect on the fuel consumption. For example, air drag is inversely proportional to the air temperature. At higher temperatures the air drag is lower, and so is the fuel consumption. Hence, the CO_2 emissions, at higher velocity where the engine power demand is dominated by air-drag were temperature corrected using the formula:

CO_2_corrected (g/s) = CO_2 * (AAT+273)/288, with AAT=ambient air temperature.

Plotting the temperature corrected CO_2 emission rates as function of velocity shows the normal third-power relation (see Figure 5.1). The offset at zero, around 0.5 g/s is related to the engine losses. The shape is related to the energy demand from air drag, which correlates with the square of the velocity. At 120 km/h, 1 kilometre takes 30 seconds, and the 4 g/s CO_2 corresponds to 120 g/km.

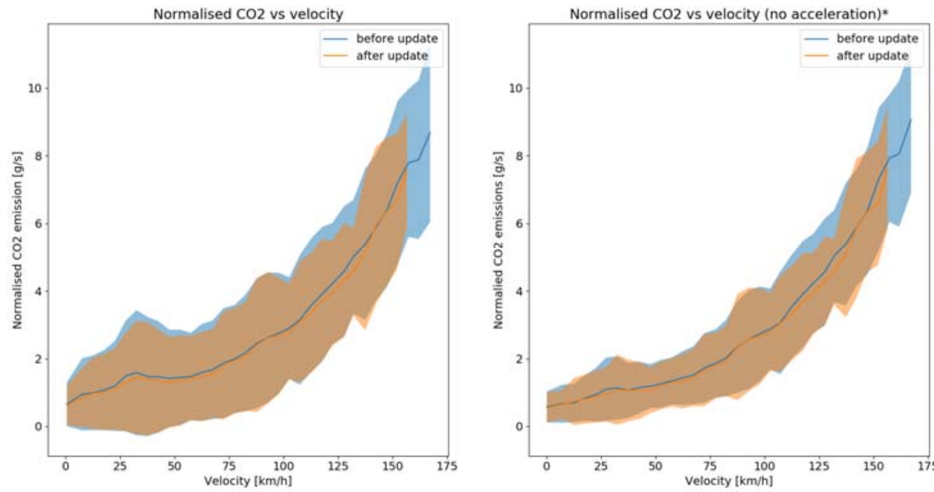


Figure 5.1: The CO_2 rate as function of velocity. Left all data, right data with limited dynamics (acceleration / deceleration no higher than 0.5 km/h/s^2). The dynamics do not increase emissions significantly but do increase the spread in emissions.

The area in Figure 5.1 with slightly lower CO_2 emissions after the update, around 120 km/h, coincides with the small area of increased NO_x emissions in the emission map of Figure 3.2 and Figure 3.3. This is an indication that at this velocity the effect of the update leads to a decrease in CO_2 emissions and fuel consumption. However, vehicle usage at this velocity may have changed as well.
Figure 5.2 shows the frequency distribution of the CO_2 emissions, but only for the data where the vehicle had a velocity between 100 and 130 km/h. The graph on the left-hand side shows all data between 100-130 km/h, the graph to the right shows only low dynamics, i.e. data for more or less constant speeds. The lines in the graphs show the average speed at any given CO_2 emission level.
The peaks in the frequency distribution are caused by constant speed driving, most likely at 100 and 120 or 130 km/h. These peaks have not shifted after the update. This means that the change in CO_2 emissions in Figure 5.1 can only be related to a change in driving dynamics i.e. acceleration. This is confirmed by the differences in frequency at the falling edge, around 6 g CO_2/s: after these updates, events with high CO_2 emission were less common, but occurred at a lower, and different, average speeds (the orange line at this interval is lower than the blue line); this indicates acceleration rather than high speed driving.

The conclusion is that the increase of NO_x emissions around 120 km/h in Figure 3.2 and Figure 3.3 can be related to an increase in driving dynamics, not to the software update.

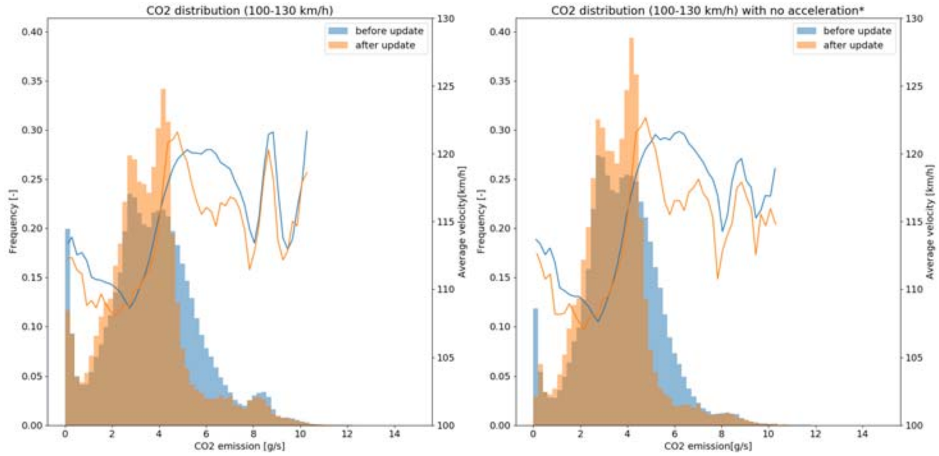


Figure 5.2: The frequency distribution of CO_2 emissions between 100-130 km/h, and the associated average velocities (lines). Left for all data, right excluding high dynamics (acceleration / deceleration no higher than 0.5 km/h/s^2).

5.3 CO_2 per revolution as proxy for torque

The CO_2 emissions per revolution are a measure of the fuel injection per stroke. This is an indication of the available torque, if the engine functions optimally. Hence the map of CO_2 emissions per revolution and the engine speed is an approximation of the engine map. Comparing these engine maps before and after the update can give an indication of changes in injection due the software update. See Figure 5.3 (before update) and Figure 5.4 (after update).

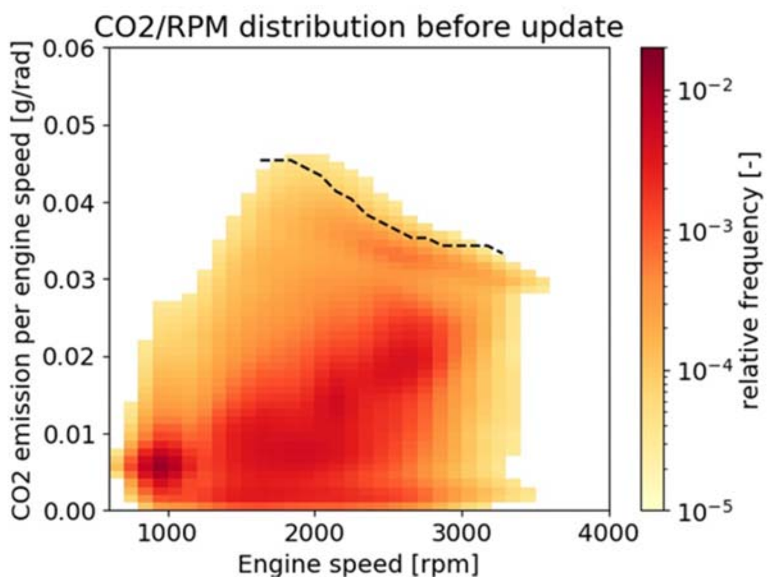


Figure 5.3: The engine map in terms of engine speed and specific CO_2 per revolution, before the software update. The unit of 0.01 g/rad corresponds roughly to 50 Nm torque. The dashed line indicates full throttle operation.

At the highest and lowest CO_2 per revolution the engine efficiency is lower than at 80% of the maximum, where the engine reaches the highest efficiency.

The sloping edge from 0.045 to 0.03 g/rad represents roughly the full throttle operation (coinciding with the maximum torque line).

Noise in the signals causes the top of the coloured patch to be an unreliable estimation of the maximum torque line. Therefore, it is difficult to evaluate any differences in vehicle behaviour from the shape of the two graphs. To overcome this limitation, the frequency distribution at the top of the graphs has been analysed. The dashed line indicates the CO_2 levels that occurred four times less frequently than the 'sand dune' just below the line and is considered an indication of the actual maximum torque curve.

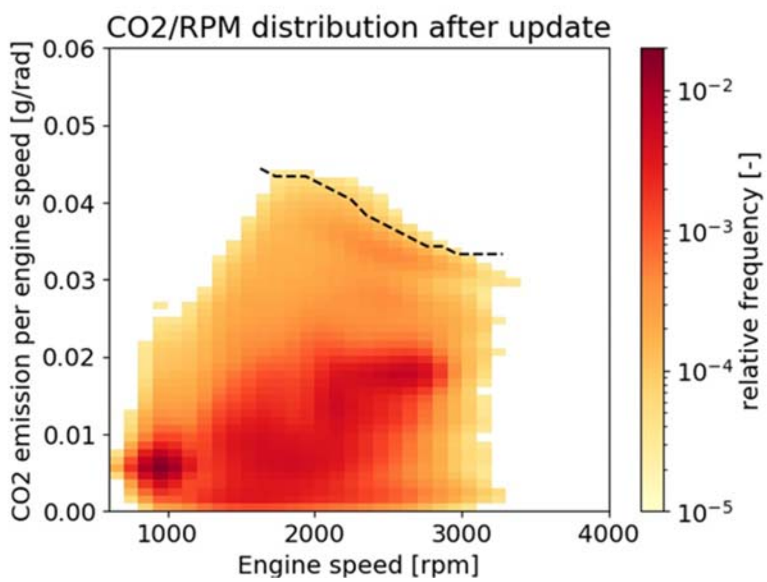


Figure 5.4: The engine map in terms of engine speed and specific CO_2 per revolution, after the software update. The dashed line indicates full throttle operation. The envelope is very similar to before the update. The frequency distribution of operation points is somewhat different, indicating a change in use.

The dashed lines in Figure 5.3 and Figure 5.4 are approximately in the same position. If the engine was quenched after the software update, the line in the second graph would have been at a lower g CO_2/rad level. There are no indications that the software update leads to reduced power in normal use.

5.4 CO_2 measurement vs CO_2 estimation from fuel consumption

Fuel consumption of the vehicle was recorded each time the vehicle was refuelled. The tailpipe CO_2 emission from the fuel consumption can be estimated knowing that 1 litre of diesel releases 2640 g of CO_2.

Comparing the stable fuel consumption over 5 consecutive refuelling events with the CO_2 measurements from the exhaust, gives a deviation of less than 4%.

6 Issues related to maintenance

Since no change in EGR rate is discernible after the software update, it is not expected that there will be more malfunctions of the EGR.

6.1 DPF regenerations

A related issue with different engine operation is the need for DPF (Diesel Particulate Filter) regenerations. The soot collected in the filter is burned off in rich operations at intervals. If more, and more persistent soot is collected in the DPF, as is understood to be the case for high EGR rates, then an increased EGR rate would affect the frequency of DPF regenerations and the duration of the regeneration. Looking at a distance of about 10,000 kilometres before and after the update, the regeneration events are easily detected from high exhaust gas temperatures, above 350°C. See Figure 6.1.

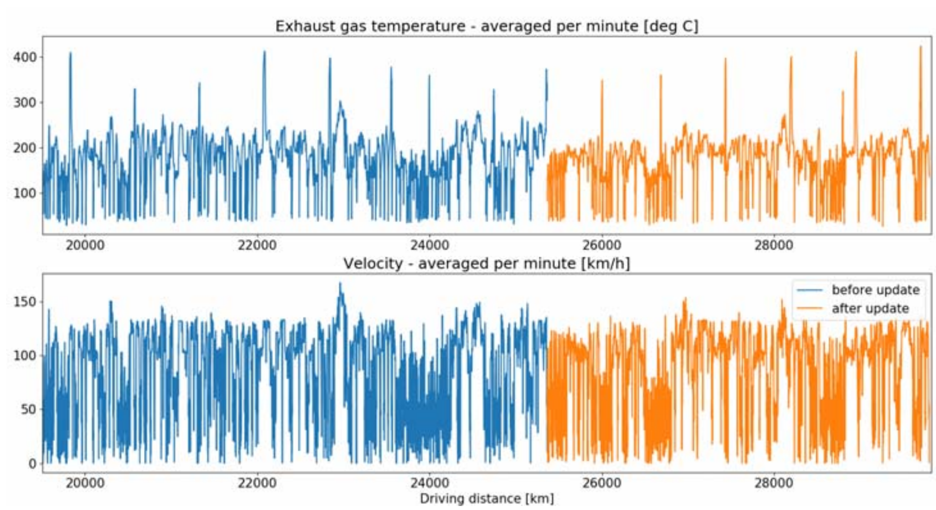


Figure 6.1: The detection of DPF regenerations from the exhaust gas temperatures. At fifteen occurrences, at regular intervals, the exhaust temperature increases, as can be seen from the top figure. Low temperatures are associated with low velocities (the velocity trace is shown in the bottom part of the figure). Regenerations require higher velocities.

The distance between regenerations is typically 750 kilometres. Only the regeneration at 24000 kilometres is associated with a much shorter distance of 445 kilometres. However, the average velocities in Figure 6.1 (bottom figure) show that in this period most driving was done at low velocity. In such urban use the DPF remains at low temperature and more soot will remain till the active regeneration. Hence, the different vehicle use explains the deviating inter-regeneration distance.

The frequency of DPF regenerations before and after the software update is not different in terms of distance. Moreover, the regenerations do not differ in duration, judged from the duration of elevated exhaust gas temperatures. Typical regenerations last 10 to 20 minutes. Only in one case the temperature was high for 31 minutes. Tracing back this regeneration it turned that after the start of the regeneration, at 100 km/h, the velocity dropped below 25 km/h a number of times.

This caused a reduced temperature and flow in the filter, requiring a much longer regeneration period than normal. See Table 6.1-1.

Table 6.1-1: The regeneration events from May 2018 till January 2019. Before and after the software update regeneration occur about once every 750 kilometres.

Location / distance between regeneration peaks and duration (between brackets)	
Before 13 Sep [km]	**After 13 Sep [km]**
21330 (@ 22 May/15 min)	26000 (reset/15 min)
22080 (+750/20 min)	26685 (+685/31* min)
22850 (+770/17 min)	27440 (+755/12 min)
23555 (+705/17 min)	28200 (+760/11 min)
24000 (+445*/16 min)	28950 (+750/15 min)
24750 (+750/15 min)	29700 (+750/10 min)
25350 (+600/11 min)	

From the data collected so far there are no indications that the engine operation after the software update leads to issues that require more maintenance.

6.2 SEMS NO_x sensor replacement

The automotive NO_x sensors used to monitor NO_x emissions with the SEMS system, are subject to wear and drift. Sensors are replaced from time to time, to be able to recalibrate them for the next use. In 2 years of operation, the SEMS NO_x-sensor has been replaced two times.

The timeline of 3 SEMS NO_x-sensors with their calibration values is shown in Table 6.2-1.

Table 6.2-1: Timeline of SEMS-NO_x sensor in vehicle and the respective calibration values

	Date of operation	Gain NO_x [-]	Offset NO_x [ppm]
Sensor 1	6 January 2017 – 2 March 2018	0.9382	2.5163
Sensor 2	2 March 2018 – 16 April 2018	0.9489	-1.866
Sensor 3	16 April 2018 – now	0.9452	-4.0413

The second replacement was done soon after the first, because an inaccurate NO_x emission signal was detected. The measurement data in the period that the second sensor was defective, is included in the data analysis, but represents only 0.9% of the data.

7 Emission tests by Deutsche Umwelthilfe

Apart from the monitoring data of TNO across the software update, other independent parties have performed dedicated emission tests with PEMS (Portable Emission Measurement System) before and after the software update. With a limited number of tests, the results may vary with the test execution and the test conditions.

Deutsche Umwelthilfe (DUH) has made their PEMS emission testing data regarding the Volkswagen software update available to TNO, at the request of the Dutch Ministry of Infrastructure and Water management. TNO has analyzed the data to correct for the differences in execution and conditions in the tests before and after the software update. The purpose of this being to investigate whether similar observations can be made on the emission performance of different Euro-5 vehicles from the same manufacturer group before and after a software update.

The Euro-5 vehicles tested by DUH were a Volkswagen Sharan 2.0 TDI, Volkswagen Caddy 2.0 TDI, Volkswagen Tiguan 2.0 TDI, Skoda Yeti 2.0 TDI and Audi A4 2.0 TDI.

7.1 Results and data normalization

If the test data is averaged for different velocities, the NO_x emissions vary greatly with velocity. The main source of this variation seems to be the differences in emissions at high and low dynamics. If the vehicle is driving constantly at a certain velocity, the NO_x emissions could be half the NO_x emissions while driving dynamically around the same velocity. Figure 7.1 shows an example of two DUH PEMS trips from Volkswagen Caddy 2.0 TDI before software update. At a velocity around 120 km/h, the difference in dynamics in the vehicle speed results in different NO_x emission behavior; higher variation in vehicle speed resulted in a higher peak in NO_x emissions, independent of the software update.

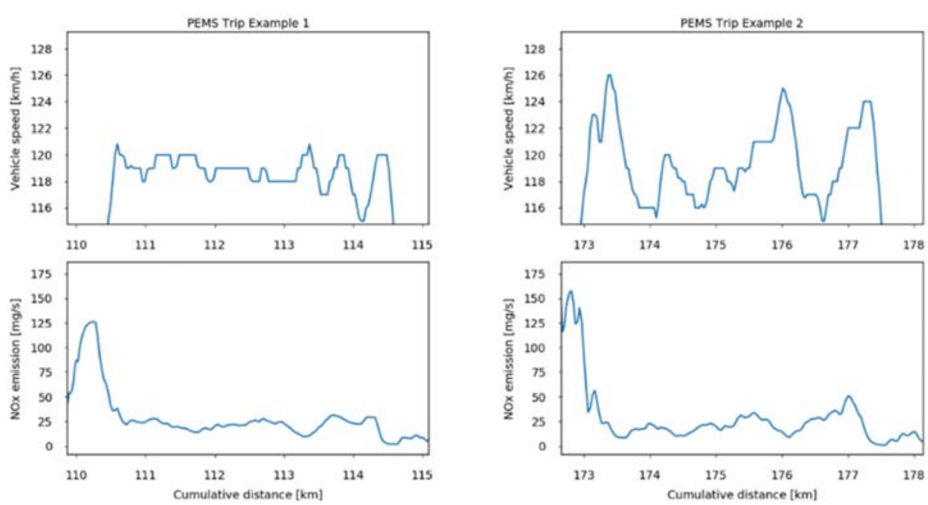


Figure 7.1: 2 PEMS trip from Volkswagen Caddy 2.0 TDI before software update with velocity around 120 km/h.

In addition to variations in NO_x emissions due to dynamics it is also known that emissions can vary based on operational conditions such as ambient temperature. As with the TNO SEMS data it was necessary to correct the data from the DUH for the variations in emissions caused by these variations in operational conditions so that the effects of the software update could be isolated. To do this a simple fitting routine was developed to correct for known variations in the different tests towards the average test operational conditions.

Important parameters in the model are the variations in fuel consumption and power demand with respect to the average dynamics.

The model to correct the data for variations in the operational conditions is a linear multi-regression fit for each velocity bin of 5 km/h separately around the average values of each parameter.

The operational parameters used are:

- CO_2 emission rate [g/s];
- Variation in CO_2 emission rate $(CO_2^{average} - CO_2)^2$ $[g/s]^2$;
- Engine speed [RPM];
- Engine Coolant Temperature [°C];
- Ambient Air Temperature [°C].

The $CO_2^{average}$ emission rate is the running average over 30 seconds. The difference between the average and the instantaneous CO_2 emission is an indication of the dynamics and variation in engine load. The time window of 30 seconds is based on the fact that this parameter varies similarly as the NO_x emission vary with velocity.

The actual corrections for varying test operational conditions are limited, given the variations in NO_x emissions for the different velocities. The corrections do tend to bring the emission results before and after the update closer together and reduce the variations between the two. The results of these corrections are presented in terms of mg/km in the figures below. This results in a singularity at zero velocity, as those emissions are associated with no distance covered.

The corrections are an indication of how the tests vary between the before and after update, relevant for NO_x emissions. For some vehicles, like the Tiguan and the Caddy these aspects seem very small, but, for example, for the Sharan, the effects are significant. However, an accurate model for correcting results needs robust data to determine the effects. With the lack of data, effects of variations in operational conditions cannot be quantified and thereby accounted for. For example, if different tests are executed at different temperatures, with little overlap in the temperatures between the tests, the results cannot be corrected for temperature effects. Such limitations show up in the Yeti data in particular.

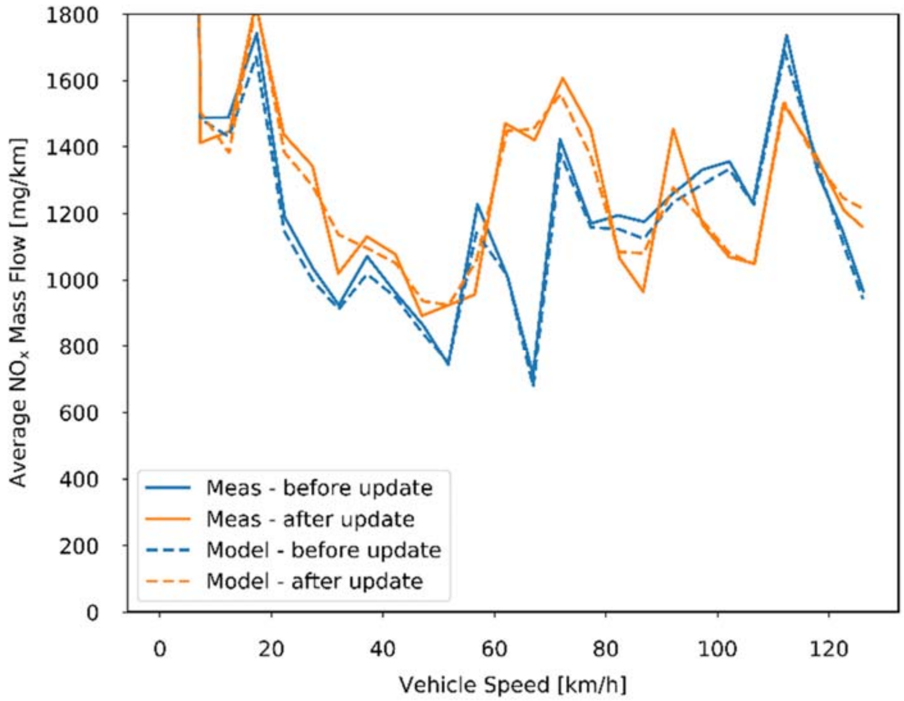


Figure 7.2: The velocity dependent emission data of the Audi A4, uncorrected, and corrected for test conditions and test execution.

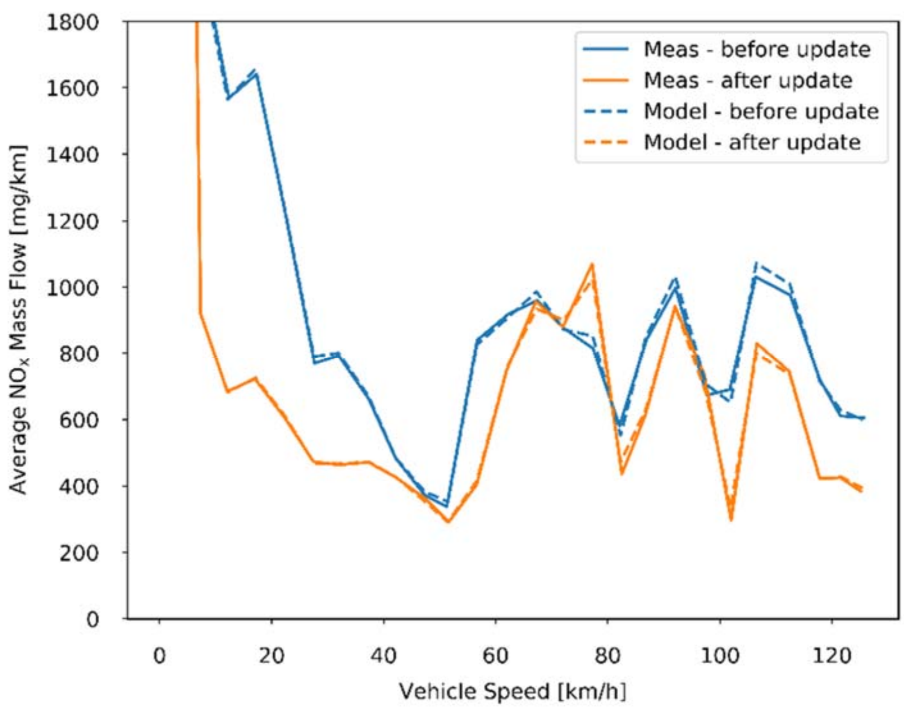


Figure 7.3: The velocity dependent emission data of the VW Caddy, uncorrected, and corrected for test conditions and execution.

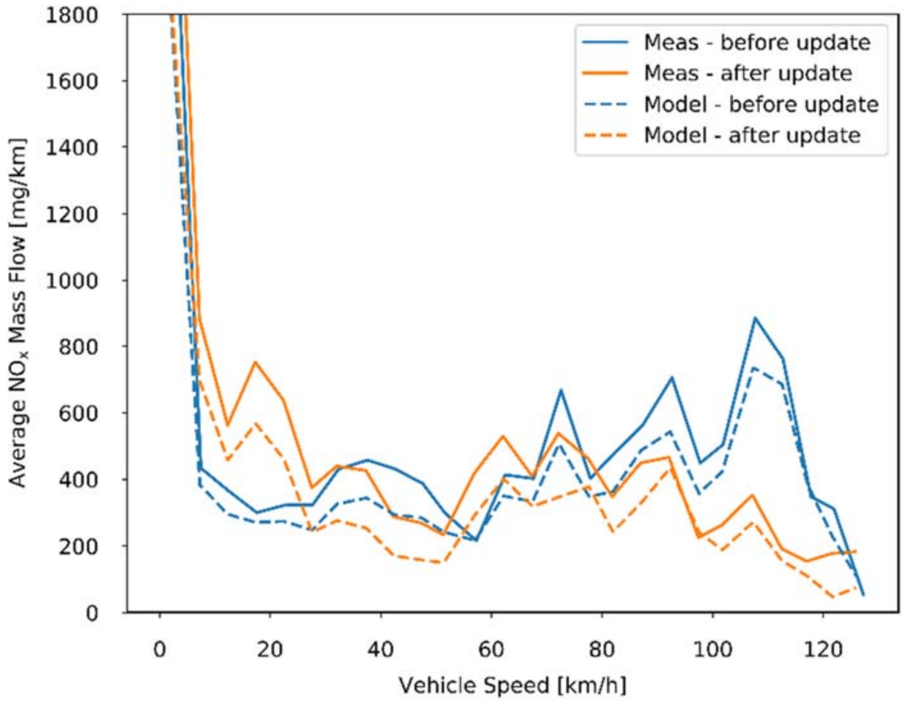


Figure 7.4: The velocity dependent emission data of the VW Sharan, uncorrected, and corrected for test conditions and test execution.

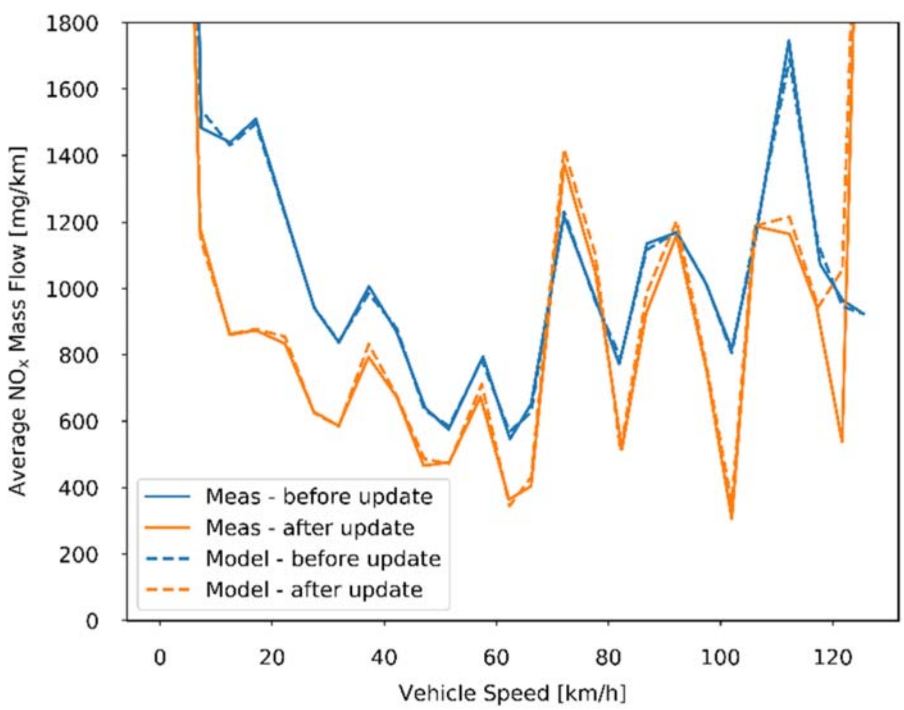


Figure 7.5: The velocity dependent emission data of the VW Tiguan, uncorrected, and corrected for test conditions and execution. The large variations with velocity yield overlapping results.

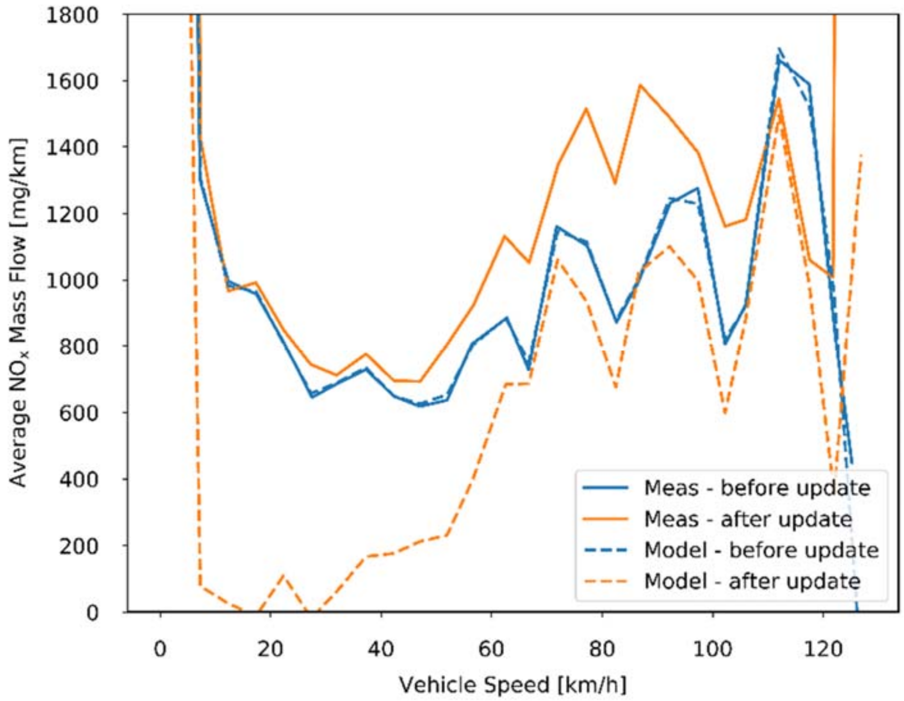


Figure 7.6: The velocity dependent emission data of the Skoda Yeti, uncorrected, and corrected for test conditions and test execution.

Figure 7.6 shows that the Yeti test results do not lead to a stable model, with large downward corrections of the test results after the update. This is mainly caused by the effects of the ambient air temperature during the measurements after the software update. The ambient temperature during these tests had a small range around 0°C. When ambient air temperature before the software update (10-15°C) was used as input for the NO_x estimation, extrapolation occurs which skew the NO_x estimation towards negative values. By excluding the ambient air temperature effect from the modelling, a stable model was achieved. More measurement data in a larger temperature range around 0°C may improve the stability of this model.

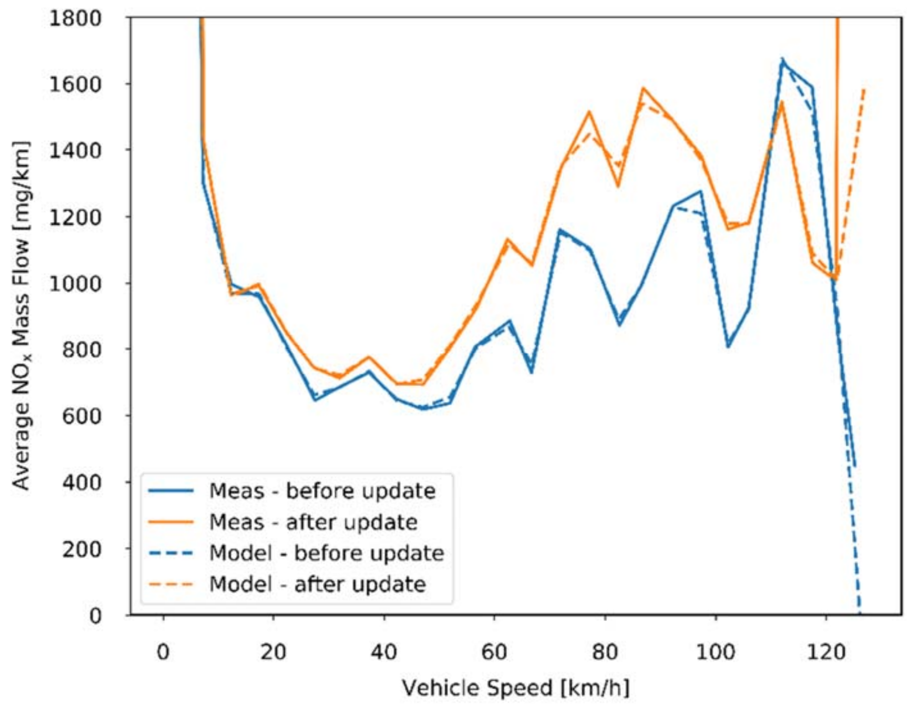


Figure 7.7: The velocity dependent emission data of the Skoda Yeti, uncorrected, and corrected for test conditions and test execution, excluding ambient air temperature from the model

7.2 Conclusions emission tests DUH

The test results of Deutsche Umwelthilfe show variable results. Both between the different vehicles, but also for different velocities for the same vehicle. Correcting for variations in test conditions and test execution gives typically minor corrections on the original result. Only the Yeti shows systematically higher emissions, over a large range of velocities, after the update, but this is very likely related to the low ambient temperature during these tests.

The presence of the variation in emission performance makes it difficult to assign a systematic effect of the software update for these vehicles. However, on average, as reported by Deutsche Umwelthilfe, the NO_x emissions of the tested vehicles after the update were slightly lower than before the update.

8 Conclusions

Over a period of two years TNO has monitored the operation and emissions of a Euro 5 VW Polo with a 1.2 l diesel engine in normal day-to-day use. During this period the vehicle has undergone a software update issued by VW in response to the diesel gate affair. The effects of the software update on NO_x emissions, fuel consumption, power and maintenance have been investigated based on monitoring data.

NO_x emissions and fuel consumption of cars depend on how vehicles are used and on ambient conditions during use. Variations in driving patterns and use conditions over time cause variations in emissions and fuel consumption. To better isolate the possible impacts of the software update from the effects of differences in vehicle usage and use conditions between the periods before and after the update, the monitoring data have been normalized. To this end the average correlations between the NO_x emissions and vehicle speed, engine power, gear shift behaviour, ambient temperature and engine temperature have been determined from the overall monitoring data. These correlations have been used to correct the emission measurement results for effects of the observed variations in use and use conditions. Variations in the residual emissions, i.e. the difference between measured emissions and the values predicted by the normalisation model which cannot be explained by variations in monitored vehicle use and use conditions, can then be associated to differences in the way the engine responds to the same vehicle usage and use conditions, before and after the update.

Caveats

- The monitoring was carried out on a single vehicle. Singular effects could therefore not be excluded. Assuming proper functioning of the vehicle and that the software update had been implemented correctly, however, the test results should be indicative of similar behaviour in other vehicles of the same model.
- The analysis was based on monitoring of real-world emissions only. No conclusions can be drawn with respect to the vehicle's emission behaviour on the type-approval test or related to type approval in general.

Conclusions

From the analysis the following conclusions can be drawn for the impact of the software update on the emissions and performance of the monitored VW Polo:

- Both before and after the update the real-world NO_x emissions are around 3.5 times the 180 mg/km emission limit applicable in the type approval test for Euro 5 diesel vehicles. These NO_x emissions are in agreement with values measured on a different Euro 5 VW Polo with the same engine in 2012, and are comparable to real-world emissions measured in the period 2010-2012 on a wider range of Euro 5 diesel vehicles of different makes and models[9];
- The software update has had no appreciable impact on the average NO_x emissions of the vehicle;

[9] See: TNO 2016 R10083 - NO_x emissions of Euro 5 and Euro 6 diesel passenger cars – test results in the lab and on the road

- In limited areas on the edges of the emission map (emission plotted as function of vehicle speed and CO_2 emission rate as a proxy for power) some changes in specific NO_x emissions can be observed. In some areas an increase is observed while in other areas emissions decrease. In both cases the changes are in the range of 20% to 40%. Specific NO_x emissions remained practically the same in the part of the emission map where the engine is mostly operated;
- Overall the software update has been found to have a negligible impact on fuel consumption and associated CO_2 emissions. Only a small decrease in fuel consumption was observed at higher speeds, of 100 km/h to 130 km/h, together with increased NO_x emissions;
- Monitoring of the CO_2 emissions per engine rotation provide an indication that the maximum power and torque were not affected by the software update;
- Monitoring of the oxygen content of the exhaust gas could give indications of changes in the use of the EGR. The same oxygen concentration before and after the update shows limited changes. On the one hand this explains the limited impacts on NO_x emissions. On the other hand, this indicates that the software update is not expected to lead to increased maintenance associated with the EGR;
- The frequency and duration of DPF regenerations was the same before and after the software update. This indicates that the update does not affect engine out emissions of soot. A change in soot emissions could be caused by changes in EGR operation. This is a further indication that the software update did not lead to increased maintenance, in this case associated with both the DPF and the EGR.

Before the software update, during one interval of the monitoring period an increasing trend was observed in the NO_x emissions which could not be explained by the known influence of vehicle usage and ambient temperature. Emission levels turned back to normal after a service event.

Test data from Deutsche Umwelthilfe covered a number of tests before and after the software update for five vehicle models. Presenting this data as a function of velocity shows the variation in the results. Given this variation makes it difficult to assign a systematic effect of the software update for these vehicles. On a whole, on average, as reported by Deutsche Umwelthilfe, the results after the update were slightly lower than before the update.

9 Discussion

The variability of emission results with vehicle usage, ambient conditions and test conditions makes it difficult to judge changes in emission performance on limited data. This study makes it clear: it is possible to monitor emission performance over longer periods, and the results of this monitoring showed the different aspects influencing the emissions. The software update of Volkswagen may have removed an illegal defeat device, but it seems to have had little effect on emission performance in normal operation.

Monitoring lifetime emissions in normal operation may be the solution to the limitations in emission testing, which are not yet fully resolved by RDE testing. The European Commission has started to look into new emission legislation, post Euro-6/VI. A shift away from testing towards continuous monitoring and taking actions on monitoring results may relieve the burden and responsibility of the manufacturer and ensure low emissions over the vehicle lifetime by proper maintenance when the need arises. If monitoring data is available in the vehicle itself, for example, from the On-Board Diagnostic system, this transparency will open new options for controlling emissions and the vehicle state.

10 Signature

The Hague, 29 November 2019 TNO

Chantal Stroek
Research Manager

N.E. Ligterink
Author