Mercedes E350T Emission System Analysis

Felix Domke – 2020/09/28

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1 Introduction, Expertise

I, Felix Domke, have been instructed to provide a report based on my expertise on the questions detailed below.

My professional experience can be summarized as follows:

- Dipl.-Ing. FH (Master's equivalent) in electronic engineering, Lübeck University of Applied Sciences, 2008
- 20 years of experience in professional development of software for embedded devices, with focus on security, security analysis and reliability
- 15 years of experience as an independent security researcher
- 5 years of experience in independent analysis of emissions-related functionality in Diesel electronic control units, including publication of peer-reviewed paper on this topic[1] and presentations[2],[3]
- Being active as an expert for the German Federal Motor Transport Authority to independently analyze software implementation in regards to defeat devices, being active as an expert and testifying as part of the parliamentary commission of inquiry in regards to vehicle emissions in 2017.

2 Abstract

Daimler AG is a multinational automotive corporation that is the manufacturer of cars sold under the brand of Mercedes-Benz. As cars are being sold to European market, they need to comply with a range of emission regulations.

Allegations have been made that a significant number of vehicles that have been successfully tested for compliance to these emission regulating rules perform very differently in normal-world scenarios, exceeding emissions by a factor of 10X.

I was instructed to provide an expert opinion on whether Mercedes cars intentionally de-rate their emissions control system during real-world driving. To do so, measurement data has been collected on a modern (2015, conforming to Euro 6 emission standard) Mercedes car, equipped with a Selective Catalytic Reaction (SCR) catalyst to reduce NO_x emissions. Additionally, the calibration data from the on-board engine ECU has been analyzed. The measurement data that was collected from the on-board engine ECU of the car during real-world driving was then correlated to the calibration data.

The result of this study is that a number of defeat devices have been identified that de-rate the efficiency of the emission control system during regular driving. These defeat devices will be discussed in detail.

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[1] M. Contag *et al.*, "How They Did It: An Analysis of Emission Defeat Devices in Modern Automobiles," *2017 IEEE Symposium on Security and Privacy (SP)*, San Jose, CA, 2017, pp. 231-250, doi: 10.1109/SP.2017.66.

2 Felix Domke, Daniel Lange, "The exhaust emissions scandal („Dieselgate")", *The 32nd Chaos Communication Congress*, 2015, Hamburg

3 Felix Domke, "Software Defined Emissions", *The 33rd Chaos Communication Congress*, 2016, Hamburg

3 Problem Statement

There have been allegations of the usage of defeat devices in Mercedes cars that correspond to the EURO 5 and EURO 6 standards. These allegations have been backed, for example by measurements of real-world driving emissions using PEMS (Portable Emission Measurement System).

While these measurements indeed show a significantly higher amount of NO_x emissions than what has been observed in standardized emissions testing (for example NEDC in a lab for homologation), they cannot – by the nature of being external – explain the difference in behavior of the car.

This report uses a different approach to explain these observed differences in emission behavior by obtaining measurements not from external sensors, but by capturing information directly from the ECU (Electronical Control Unit) that controls the engine and emissions management.

This gives a different view on the data – instead of treating the engine, engine controlling software and the emission control system as a black box, and only observing the inputs (such as ambient temperature and vehicle speed) and outputs (emissions as measured by external sensors in the PEMS device), this approach can show intermediate data that is used internally in the ECU to control and steer the engine behavior and emissions.

Because such internal behavior is typically not documented by the car manufacturer, existing diagnostic facilities, together with detailed information about the software, have been used to obtain and analyze the data.

In view of the amount of work involved in this investigation, only one vehicle has been analysed. However, the Kraftfahrt Bundesamt has identified defeat devices in a wide range of Mercedes vehicles. It is my opinion within a reasonable degree of engineering certainty that other Mercedes vehicles with comparable engines and techniques contain comparable defeat devices.

4 Methodology

The methodology used in this report is a combination of data collection, behavioral analysis (with referencing calibration data) and interpretation of the results.

Because of the complexity and the amount of present information channels from the ECU (an ECU internally processes in the order of more than 10000 signals) an iterative process has been used. As a first stage, broad data collection has been used to profile the car during regular operation. After analyzing the bulk collected data, data sections have been identified that are related to the emissions control systems. Data collection has then been fine-tuned to provide higher-resolution data.

4.1 Data Collection

Data collection has been done over the OBD-2 port. This port, located in the front left of the driver compartment, is a standardized interface that allows the diagnostic tester to interface with the car and the on-board ECUs. Using ECU-specific commands ("UDS ReadMemoryByAddress"), data internal to the ECU can be read and logged. A custom device has been built that continuously reads out such data and logs it to a storage medium. The bandwidth of the OBD-2 interface is limited, so depending on how much data is being read, a full set of data can be obtained every few minutes (if reading out all available information), or every few seconds (when limiting data selection to emissions-related areas). Using an iterative process, the analysis has resulted in a minimized set of memory locations that still convey all necessary information for the interest of understanding the potential employment of defeat devices.

4.2 Software Analysis

The software of the ECU (Bosch EDC17CP57) has been obtained by reading out the ECU using a third-party tool ("FLEX", developed and sold by Magic Motorsports). Using the firmware and existing documentation of similar Bosch ECUs allowed to first understand the general structure of the emissions control system, and allowed to derive the exact location of both calibration data constants as well as measurement points within the software. This allows to use existing data and calibration analysis tools on this software.

4.3 Behavioral Comparison

Two software versions have been compared:

1. Original software: The software that was originally installed ("CR61-GDB2-212SA-642LS-EU6OPS_4x4_3S_NAG2-ME10<-> (13.07.2015 08:30:25)")
2. Updated software: An updated software ("CR61-GHB0-212SA-642LS-EU6OPS_4x4_3S_NAG2_VarB-ME21") that was installed to the ECU to analyze the behavior of the 2020 software update.
   Before installing the updated software, the original ECU was cloned in order to leave the integrity of the original ECU intact. After verifying functional correctness of the cloned ECU, the cloned ECU was then updated with the new software.

By comparing the behavior of the software during similar driving conditions, and correlating these behavioral changes with changes observed in the software and parameters, the differences between software versions can be shown.

5 Limitations of the described approach

By the nature of the described approach, only sampled data of real-world driving situations is available. All data has been captured from a single car. In general, no attempt has been made to correlate the driving behavior to an existing test standard (like RDE), but it has been attempted to cover typically used scenarios (inner-urban, extra-urban, highway) at different conditions. No specific testing on a chassis dynamometer has been done.

A single car has been selected for the tests:

Car Type: Mercedes E 350 BlueTEC 4MATIC T

Engine: OM642, 190kW, 2987 ccm, 6 cylinders

[redacted]

Model Year: 2015 (initial registration: 1/2016)

The car has been verified to not have any pending faults indicated by the on-board diagnostics.

6 General

The analyzed car uses multiple strategies to reduce the amount of NO_x emissions. In this case, the algorithms and parameters for EGR (Exhaust Gas Recirculation) and SCR (Selective Catalytic Reaction) have been analyzed. Additional factors for NO_x emissions exist, but EGR and SCR have been prioritized as they are most relevant.

In the Selective Catalytic Reaction for reducing NO_x emissions, one of the most important control variables for SCR is the amount of DEF (Diesel Exhaust Fluid, also called by the brand-name *AdBlue*, or more generic *reduction agent*) dosing. On the car in question, the Engine ECU, a Bosch EDC17CP57, controls in real-time how much DEF (if any) is being added into the system.

Within the SCR catalyst, the DEF is converted to ammonia, and reacts with the (and Oxygen) NO_x to Nitrogen and Water.

The measure of effectiveness is the “SCR removal efficiency” or “conversion efficiency”, which is the ratio of NO_x that is removed from the exhaust gas.

Physical conditions place an upper boundary on how effective the SCR system can be. Mostly, SCR performance is limited by the following phenomena:

- If the SCR temperature is too low, injected DEF does not convert to ammonia.
- If the SCR temperature is too high, ammonia will oxidize directly.
- If the exhaust mass flow is too high (i.e. the exhaust speed is too high), the exhaust gas will not have sufficient time to react with the SCR catalyst.
- Similarly, if the NO_x mass flow is too high, the SCR cannot reduce all of the NO_x.

For more details, specific SCR literature should be consulted. This list is non-exhaustive but shows that there are legitimate physical limitations of an SCR system.

The SCR system in the tested car is designed to operate in one of two modes:

6.1 The Ammonia Load Model

An SCR system is most efficient when enough ammonia is present in the SCR catalyst. In conditions where the temperature of the SCR catalyst is too low to allow thermolysis of AdBlue to ammonia (around ~150 °C), it is not possible to increase the ammonia concentration by adding more AdBlue.

The SCR catalyst however has the ability to store excessive ammonia up to a certain point. This property can be exploited by filling the catalyst with ammonia. This is done by dosing more AdBlue than what would be stoichiometrically required to reduce the current NO_x load. In that case, extra ammonia will be left over which then remains in the SCR catalyst.

Because the SCR catalyst has an upper limit of ammonia storage, when the SCR catalyst is fully loaded, excessive ammonia will leave the catalyst and produce ammonia slip, which needs to be avoided. In order to not over-fill the SCR catalyst, but still keep the SCR catalyst sufficiently filled whenever possible, the state of SCR catalyst (amount of ammonia, reaction rate etc.) needs to be known to the ECU software. Because no sensors exist that can directly measure this state, modelling is used instead. The ECU has been carefully tuned to predict the behavior of the SCR catalyst based on input variables. A NO_x

sensor at the output of the SCR catalyst is used to verify and fine-tune the model during regular operation, producing the very accurate model required to dose the right amount of AdBlue.

By utilizing the ammonia load model, the SCR catalyst can be kept filled most of the time, resulting in very efficient NO_x reduction, often exceeding 95% (i.e. removing >95% of NO_x), as required by the emission standards.

As any other model, this model is only an approximation of the real physical behavior. Within known limitations, the model can be shown to work very accurately. However, in more extreme cases, for example during high operating temperatures, high exhaust mass flow, high NO_x concentration, the model is not sufficiently accurate anymore. Relying on the ammonia load model in this case would risk over- or under-dosing of AdBlue, which would result in either ammonia slippage or insufficient NO_x removal.

The on-board diagnostic of a car is required to detect these conditions, and is required to illuminate the "Check Engine" light. Depending on how bad the detected issue is, it can also prevent the car from operating at all. For example, if instead of AdBlue, water is filled into the AdBlue tank, the on-board diagnostics are required to sense this and prevent starting the engine eventually.

In the context of potential defeat devices, as long as the ammonia load model is active, and programmed intentional deviation (for example due to a defeat device attempting to limit AdBlue consumption) from the "ideal" dosing would result in such detected over- or under-dosing. While it would be possible to also manipulate the monitor process, this would have a significant impact on the overall operation. No observation of usage of defeat devices on this car in the ammonia load model have been made.

6.2 The Alternative Model

As described, exceeding certain physical limits can reduce the accuracy of the ammonia load model to the point where over- or under-dosing is risked. To remedy this problem, Bosch (and many other ECU manufacturers) implemented an alternative control strategy which is vastly simplified. This alternative control strategy is called "Alternative Model" in this report, but other names that have been used include "Pre-Control", "Online-Dosing", "Feed-Forward" etc.

In this mode, no attempt is made to keep the SCR catalyst at high ammonia levels. Instead, AdBlue is dosed at the amount that is needed to reduce the current load of NO_x only. The calculation for the amount of dosed AdBlue is done stoichiometrically based on the estimated NO_x load, reduced to the "expected efficiency".

The "expected efficiency" is a factor (between 0 and 1) which indicates how much of the NO_x can be removed. In ideal conditions, this reaches a very high number (>0.95), but depending on operating conditions, the ECU calculates a much lower "expected efficiency". A central observation of the analyzed car is that this "expected efficiency" – probably better described from now on as "target efficiency" – is held at a relatively low value in many driving conditions.

In the alternative model, the ECU does not attempt to reduce more NO_x than what is given by the target efficiency, as the amount of AdBlue that is dosed in reduced accordingly.

Internally, many factors are combined to produce the “target efficiency”. The calculation starts with a factor of “1” (meaning that theoretically all NO_x can be reduced), but then applies a number of correction factors (all between 0 and 1) that are multiplied together. These correction factors are based on evaluating a number of conditions that are expected to reduce the possible reduction rate.

The observation in this car is that additional factors are employed that cannot be described to be based on physical limitations – i.e. the “target efficiency” is intentionally de-rated to a lower value depending on inputs that should not directly affect the NO_x reduction in the SCR catalyst, i.e. factors that do not resemble physical limitations, but rather are based on policies. These reductions, which can be described as defeat devices, will be described further.

7 Defeat Devices

Different defeat devices are employed in the analyzed car. For SCR, these defeat devices have the following properties in common:

1. They trigger on physical properties that are generally needed to be monitored for extreme conditions, such as temperature, mass flow etc.
2. However, they trigger routinely in what can be considered as normal “real-world” driving conditions.
3. They are designed to have an effect well after being “triggered”, for example by using a large hysteresis and or employing a “restart protection” (see below).
4. They greatly reduce the internal efficiency estimation of the SCR system, which drastically reduces AdBlue dosing, which in turn generates a much higher NO_x output.

In total, six defeat devices were identified that relate to the SCR-system. Three of these defeat devices are subject to an “aging factor” that significantly lowers the thresholds at which these defeat devices are activated. For two of these defeat devices, this happens at an aging ratio of 1% (i.e. very early in the lifetime of the vehicle) and for another at 20%.

In addition, two defeat devices were identified that relate to the vehicle’s EGR-system that are triggered in circumstances where a physical justification is lacking. When triggered, they reduce the operation of the EGR system significantly.

The updated software uses optimized thresholds that produce a much-improved NO_x performance, showing that the car hardware is indeed much more capable. In the updated software, the defeat devices are either neutralized or removed in their entirety.

7.1 Test Cycle Behavior

No specific testing on a chassis dynamometer was performed on the analyzed car. From observation of real-driving patterns that mimic those which are tested within the NEDC, certain predictions about the behavior of the car during a test cycle can be made.

For some of the defeat devices, such as the intake air temperature switch, it is clear that these are not triggered during a test cycle because the limits are clearly specified in the testing regulations, or because the aging factor that triggers their increased operation has likely not been reached at the moment of testing. For other defeat devices that depend on the dynamic behavior of the car, it is the expectation that these are not triggered during the test cycle, based on the predictions from regular car usage.

7.2 Physical Limitations vs. Parameterization of the defeat devices

It is noteworthy that some of the defeat devices are parameterized to enforce “switch” to a less efficient emission mode at a specified threshold.

8 Defeat Device #1: Exhaust Gas Mass Flow Limit

8.1 Background

Exhaust mass flow is the measurement of the amount of exhaust gas (burned and unburned fuel and air) over time. The unit used in this paper is kg/h. The amount of exhaust mass flow is correlated with the speed of the exhaust gas through the catalyst, and as such directly related to the time that is available in the SCR catalyst to cause the NO_x reduction reaction to happen. The engine ECU needs to track the exhaust mass flow to detect SCR efficiency loss due to insufficient reaction time, and prevent over-dosing of ammonia. As such, exhaust mass flow is a legitimate physical quantity that needs to be modelled (or measured) and taken into account when calculating the SCR efficiency.

The SCR catalyst should be constructed to have a sufficient size (i.e. reaction chamber) that SCR efficiency can be maintained at a satisfying rate during regular car operation. If the SCR catalyst is designed as too small, a reduction of the SCR efficiency at higher engine rpm can be expected.

8.2 Summary

A defeat device activates the Alternative Model when the exhaust mass flow exceeds a pre-determined level (which depends on SCR aging). In real-driving scenarios, this limit was observed to be exceeded typically around 100 km/h. Once in the Alternative Model, a mechanism restricts the target efficiency to less than 60% in the majority of operating conditions.

8.3 Details

As explained above, when the exhaust mass flow exceeds what the SCR catalyst can handle, exhaust gas can escape the SCR catalyst without having had a chance to be fully reduced. If unhandled, this would lead to an over-estimation of the SCR efficiency, causing over-dosing of AdBlue/ammonia, and would yield excessive ammonia in the catalyst which would yield to ammonia slip. It seems a valid strategy to observe the mass flow, and reduce the estimation for the SCR efficiency if excessive mass flow is detected. Further, it is reasonable to assert that the SCR efficiency cannot be estimated accurately enough for the ammonia load model anymore in this case, which requires a switch to the alternative model. Such mechanism in itself can be required even in state-of-the-art emission control systems and is generally not seen as an illegal defeat device because it is the direct result of a physical limitation.

In the case of the tested car, the limit however was observed at 170 kg/h – that is, if the filtered (i.e. smoothed-out) exhaust mass flow, measured in kg/h of exhaust gas, is exceeded, a switch to the alternative model is enforced. Further, a strong hysteresis (of -80 kg/h) is applied so that a switch back to the load model requires the mass flow to be below 90 kg/h, which is routinely exceeded even driving at lower speeds around 60km/h.

The exact limit is a function of an "SCR aging factor". The aging factor is a percentage, where 100% corresponds to a new catalyst, that is gradually de-graded (down to eventually 0%) over time. For this, the engine ECU tracks the temperatures that the SCR catalyst has been exposed to, and models the effect of aging. The tested car has an internal aging factor of ca. 69%.

It is noteworthy that the switch from 200 kg/h to 170 kg/h happens at an SCR aging factor of 99%, i.e. only very new SCR catalysts will use a limit of 200 kg/h.

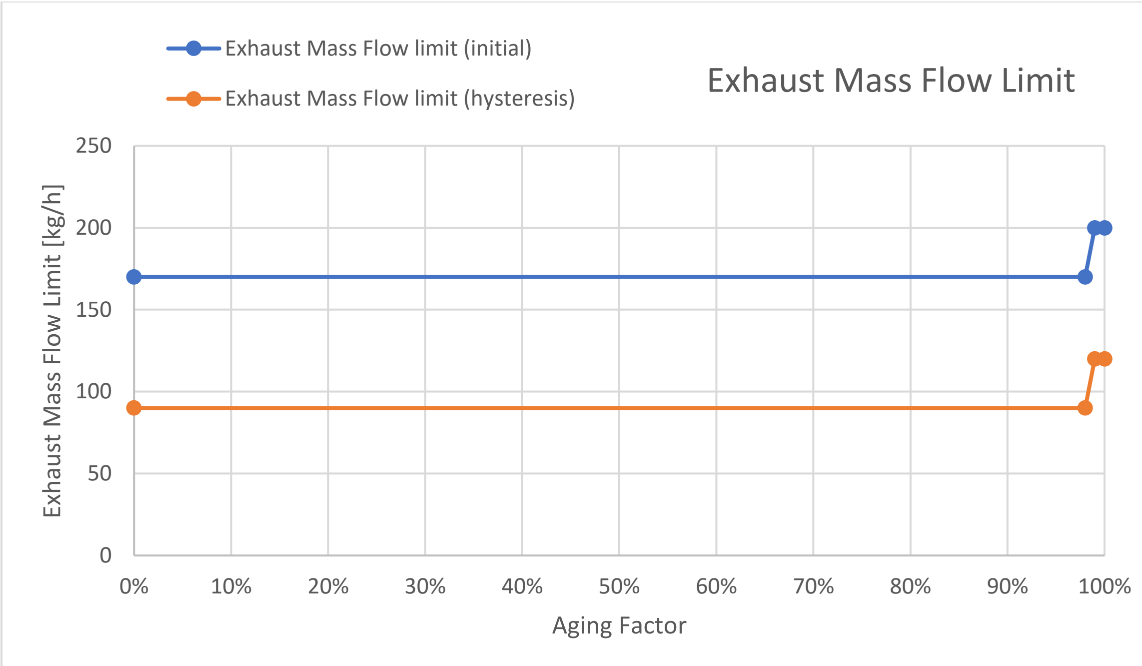

Figure 1 - Exhaust Mass Flow Limit as a function of SCR aging factor, extracted from calibration data of the original software. At an aging factor of 99% the threshold is lowered from 200 kg/h to 170 kg/h. The lower bar indicates the hysteresis limit, i.e. when the initial limit was exceeded once, the mass flow needs to be below 90kg/h (or 120 kg/h for new SCR catalysts). (The internally tracked aging factor is a function of the conditions that the SCR catalyst was exposed to; thereby no simple aging-factor-to-time relationship exists.)

Because the mass flow rate is filtered, idling the engine for a short amount of time will not directly switch back.

Exhaust mass flow rate is strongly depending on driving conditions. To estimate the effect for real-world driving, the diagram below shows typical (i.e. observed in regular driving scenarios, typically on flat roads) exhaust mass flow rates depending on vehicle speed. This is an estimation only, as exhaust mass flow rate will also strongly depend on requested torque due to acceleration, road grade and vehicle mass. But it can be seen that when driving faster than ~100 km/h it is highly likely that the upper threshold will be exceeded, forcing a switch to the alternative model. At that point, the lower threshold will become active, making it difficult to switch back in normal driving.

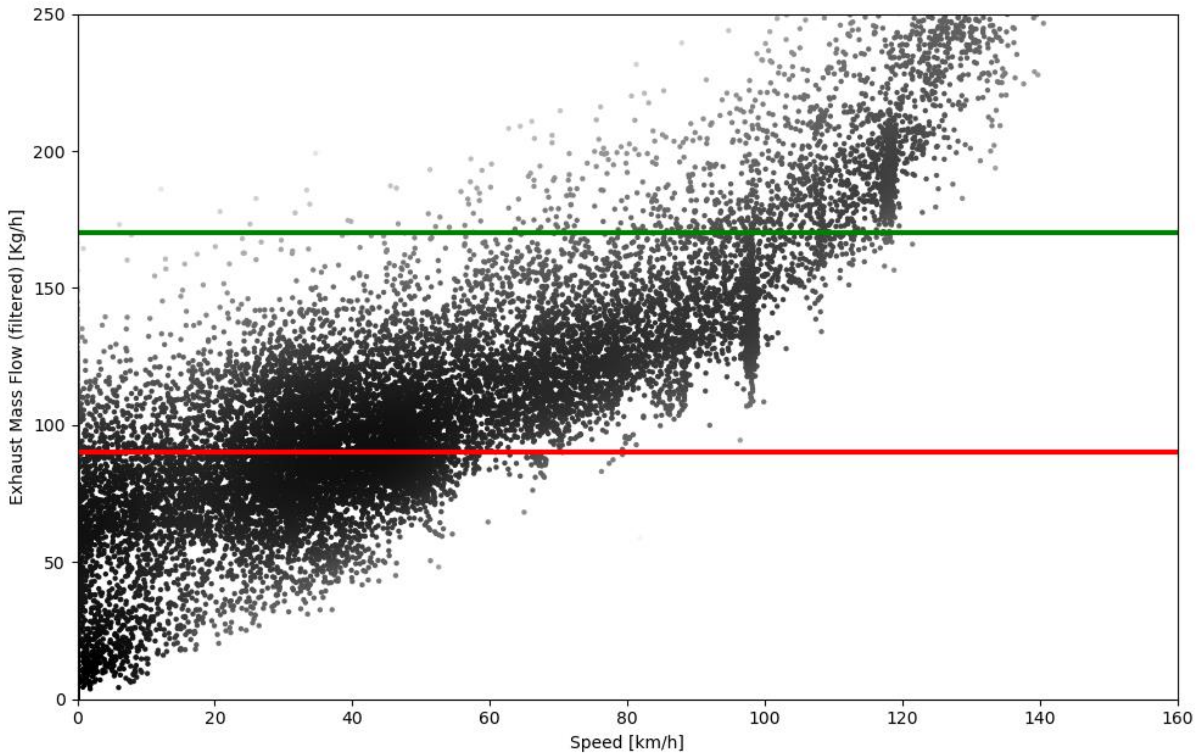

Figure 2 – Measurement data of observed Mass Flow (filtered) in Real-World Driving as a function of vehicle speed; the red and green bars indicate the limits for the "Exhaust Gas Mass Flow Limit" defeat device (green – initial limit, red – limit after being enabled due to hysteresis). It can be seen that typically between 100 km/h and 120km/h the limit (170 kg/h) is exceeded. Once the limit is exceeded, the lower bar limit activates.

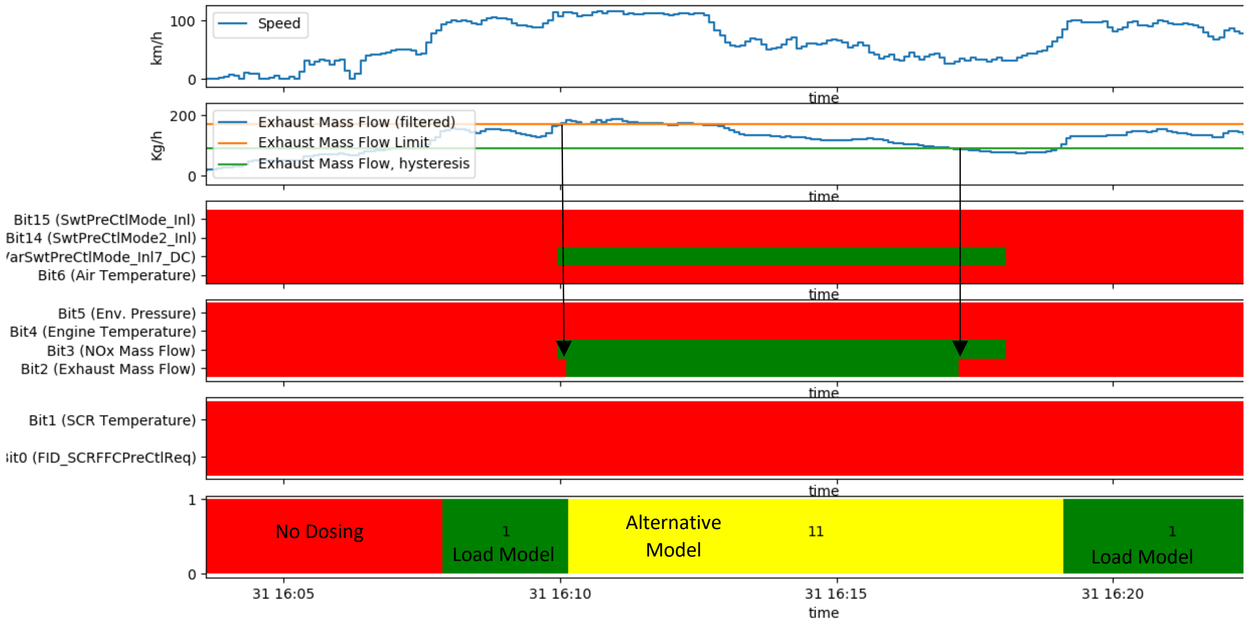

Figure 3 – Measurement data with original software; Two events visible: at around 16:10 (left black arrow), the exhaust mass flow exceeds the limit of 170kg/h, causing the defeat device to activate, enforcing a switch to the Alternative Model. At around 16:17 (right black arrow), the defeat device deactivates, eventually allowing a switch back to the Load Model. (Other defeat devices, for example the NO_x mass flow limit, activate at the same time.) Bit names refer to the bit positions in the "prectl2"-Mode word that ECU software uses to determine when to switch to the alternative mode.

8.4 Behavior in Alternative Model

Once switched to the Alternative model, the estimated efficiency is reduced by a factor that is looked up from a map. The inputs to the map are the exhaust gas mass flow and the SCR temperature. The efficiency correction is multiplicative – i.e. if the estimated efficiency is 80% before, and the map defines a factor of 60%, the resulting efficiency would be calculated as 60% of 80% = 48% etc. The table below shows this map – it can be seen that in most operating conditions, the estimated efficiency peaks at 60%. This means that even if all other conditions are perfect, no attempt is made to remove more than 60% of the NO_x emissions.

		Mass Flow [kg/h]											
		50	75	100	150	180	200	225	250	300	500	600	700
SCR Temperature [°C]	130	9%	9%	9%	8%	8%	8%	8%	7%	7%	6%	6%	5%
	160	18%	18%	17%	17%	17%	16%	15%	15%	14%	14%	11%	8%
	180	25%	24%	23%	23%	22%	21%	20%	19%	18%	17%	15%	11%
	200	34%	33%	33%	32%	32%	31%	29%	29%	27%	24%	19%	14%
	225	60%	60%	60%	60%	60%	60%	58%	45%	38%	33%	25%	19%
	250	60%	60%	60%	60%	60%	60%	58%	55%	51%	41%	32%	25%
	280	60%	60%	60%	60%	60%	60%	60%	60%	55%	45%	36%	28%
	300	60%	60%	60%	60%	60%	60%	60%	60%	55%	45%	65%	75%
	380	60%	60%	60%	60%	60%	60%	60%	60%	55%	45%	65%	75%
	400	60%	60%	60%	60%	60%	60%	60%	60%	55%	45%	40%	35%
	480	60%	60%	60%	60%	60%	60%	60%	60%	55%	45%	40%	35%
	500	75%	75%	75%	75%	75%	75%	75%	75%	60%	45%	40%	35%

Figure 4 - Efficiency Correction map via SCR-Temperature and Mass Flow, extracted from calibration data of original software. Reading example: At a mass flow of 150 kg/h, and an SCR Catalyst temperature of 250°C, the efficiency estimation would be reduced to 60% of the original value (i.e. by factor of 0.6x).

While operating in the Alternative Model already reduces the efficiency of the SCR system by the nature of not attempting to store excessive ammonia in the catalyst for use on demand, this map further reduces the target efficiency to peak out at 60% (aside from very high load, high temperature driving conditions where 75% is encoded). **This means that once the Alternative Model is activated** – only in this mode does the map take any effect – **the ECU never attempts to supply sufficient AdBlue to reduce more than 60% of the NO_x load** (outside of the discussed special case of very high mass flow).

While this efficiency correction map is the one that most drastically reduces SCR performance while in the alternative model, other efficiency corrections are applied on top of this map, and may further reduce efficiency.

8.5 Changes via Software Update

The mechanism was changed in the following aspects:

1. Exceeding a Mass Flow limit will not anymore switch to the alternative model.
2. The efficiency correction map – still used when the alternative model is selected by a different criterion – was updated to the following table:

		Mass Flow [kg/h]											
		25	50	100	150	175	200	225	300	400	500	600	800
SCR Temperature [°C]	100	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%
	150	20%	20%	20%	20%	20%	20%	20%	20%	10%	10%	10%	5%
	175	45%	45%	45%	45%	45%	45%	45%	25%	15%	10%	10%	5%
	200	50%	50%	50%	50%	50%	50%	50%	35%	20%	12%	10%	5%
	225	60%	60%	60%	60%	60%	60%	50%	40%	37%	33%	25%	10%
	250	75%	75%	75%	75%	75%	75%	70%	58%	55%	50%	40%	20%
	275	85%	85%	85%	85%	85%	85%	85%	75%	63%	55%	50%	25%

	300	90%	90%	90%	90%	90%	90%	90%	85%	65%	60%	60%	30%
	350	95%	95%	95%	95%	95%	95%	95%	95%	75%	60%	60%	30%
	450	95%	95%	95%	95%	95%	95%	95%	90%	75%	60%	60%	30%
	550	80%	80%	80%	80%	80%	80%	80%	80%	50%	40%	40%	20%
	650	50%	50%	50%	50%	50%	50%	50%	40%	20%	10%	10%	10%

Figure 5 - Efficiency Correction map via SCR-Temperature and Mass Flow, extracted from calibration data of updated software.

8.6 Limitation of the Analysis

Exhaust mass flow is the sum of fuel and air that discharged from the engine. The amount of injected fuel depends on the torque set point as well as any additional exhaust heat requests, and as such is depending on the exact driving situation. A strong correlation to vehicle speed exists, but many other factors – such as how quickly the car is accelerated, the properties of the road and also ambient conditions – exist. The exhaust mass flow quantities that have been observed for this report are samples, and may not generally reflect the situation on other cars, other driving situations or other ambient conditions.

The effect of SCR catalyst aging could not be measured on the tested car, as the tested car was purchased with the SCR catalyst aging factor already below the encoded switch value. As such, only the lowered threshold was used by the original software. The threshold of the aging factor is set at 99%, thereby indicating that the switch to the stricter mass flow limit happens very early in the lifetime of the catalyst, but the analysis approach did not allow this to be quantified in time or mileage.

The aging factor is an internal representation and does not necessarily reflect the real age of the catalyst (as measured in time or mileage), but is rather a representation for the amount of wear to the catalyst, based on the environmental conditions that the SCR was exposed to in its lifetime.

9 Defeat Device #2: NO_x Mass Flow

9.1 Background

The SCR catalyst has a given capacity for reducing NO_x. Excessive NO_x mass flow will at some point inhibit the ability for the catalyst to fully reduce NO_x. Similar to the discussion for exhaust mass flow, this effect must be taken into account to avoid the risk of over-dosing AdBlue, yielding ammonia slip.

The amount of NO_x that is produced "upstream", i.e. before the SCR catalyst, is – under the absence of other post-engine NO_x reduction methods – directly related to the operating conditions of the engine. EGR, injection timing, rail pressure and other factors are used to balance keeping the NO_x emissions low versus other factors such as reducing particulate matter, fuel efficiency and subjective drivability.

9.2 Details

As it can be seen in the diagram below, the NO_x generated by the engine strongly depends on driving behavior, and usage of EGR (and other NO_x reduction techniques) in the engine. Nevertheless, a correlation between vehicle speed and NO_x emissions exists, even though other factors (such as acceleration profiles) largely affect NO_x emissions as well. The next diagram shows observed NO_x emissions, measured in mg/s, relative to vehicle speed.

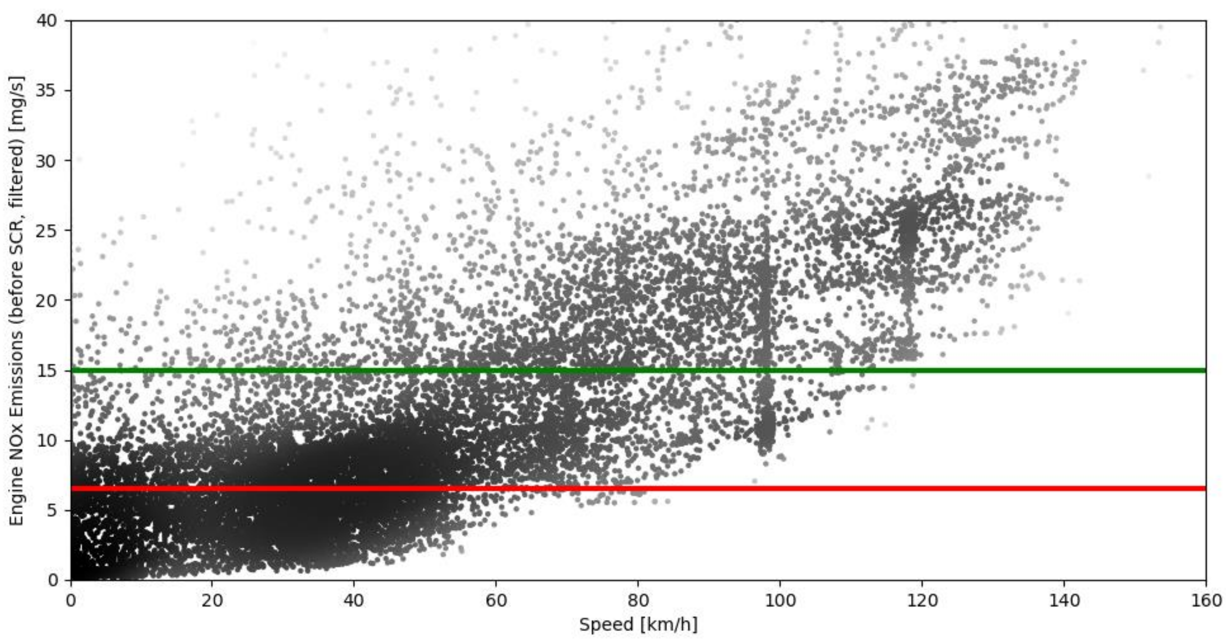

Figure 6 – Measurement data with original software: observed raw NO_x emissions during Real-World driving; the initial threshold is marked in green, when exceeded the lower threshold (marked in red) will activate (hysteresis).

In the tested car, a defeat device was found that will enforce the alternative model when the NO_x mass flow exceeds a calculated threshold. The threshold – observed at 15mg/s is marked in green in the diagram. A switch back to the load model is only allowed when the low limit of 6.5mg/s is undercut (hysteresis).

The threshold is depending on the discussed "SCR aging factor". Noteworthy again is that the threshold is initially set to 25 mg/s, but then ramps down to 15 mg/s at an aging factor of 99%, i.e. after very little computed "aging".

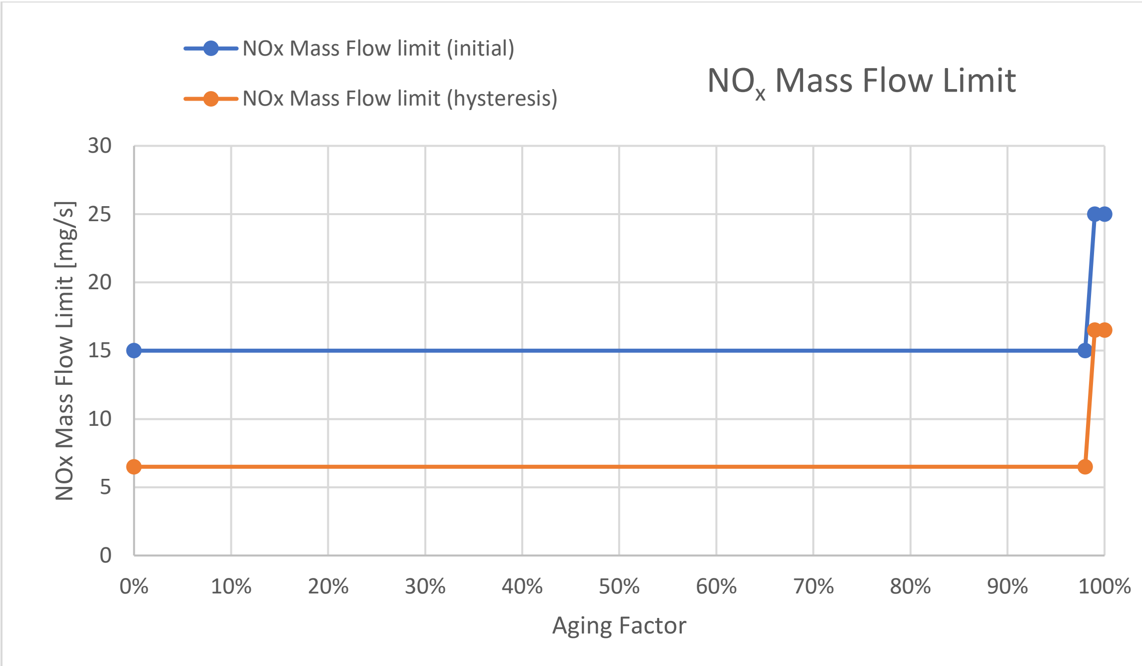

Figure 7 - NO_x Mass Flow Limit as a function of SCR catalyst aging, extracted from calibration data of original software. The upper (blue) line describes the initial threshold to switch to the Alternative Model, the lower limit describes the threshold that allows switching back (hysteresis).

This means that on excessive NO_x production by the engine, the SCR system is *further* limited in reducing these emissions only to a lower percentage, producing even larger emissions.

The heavy use of hysteresis must be noted here – once the limit of 15mg/s is exceeded once, the very low limit of 6.5mg/s must be achieved first to switch back, which in typical driving scenarios is often hard to do. While vehicle speed is correlated to NO_x mass flow, other conditions (such as acceleration profile) significantly affect NO_x emissions, which does not allow to describe this limit as a function of typical vehicle speed well. The distribution of observed NO_x mass flow quantities from the figure above can be used to evaluate the occurrences of such switches.

Once the Alternative Model is enforced, the SCR efficiency is already limited due to the discussed "Exhaust Mass Flow/SCR Temperature" correction map, which is active in the alternative Model regardless of the switch criteria. In the Alternative Model, an additional correction factor is calculated based on the filtered NO_x mass flow. The curve is configured so that when exceeding 40mg/s of NO_x, the target efficiency is further reduced pretty drastically.

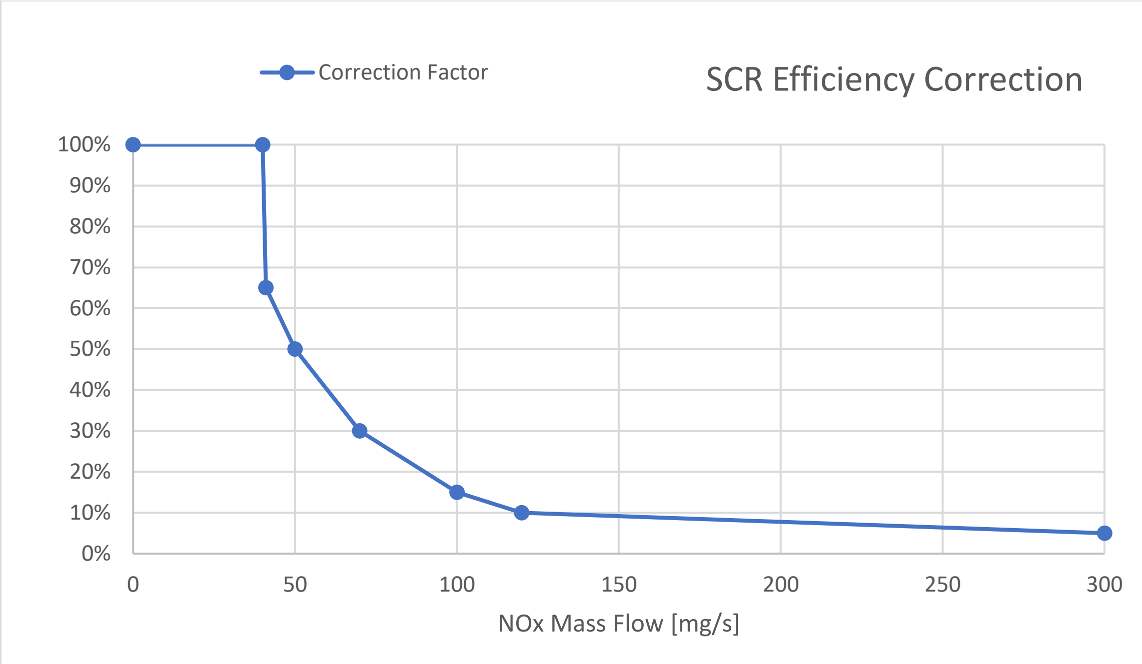

Figure 8 - SCR efficiency correction factor as a function of NO_x mass flow, extracted from calibration data of original software.

9.3 Changes via Software Update

- The change to the alternative model due to NO_x mass flow has been completely removed. NO_x mass flow is still taken into account for calculating the expected SCR efficiency (and thereby controlling the AdBlue dosing), but the alternative model is not enforced anymore as the result of exceeding NO_x emissions.

9.4 Limitation of the Analysis

The amount of NO_x produced in the engine depends on the amount of fuel burned as well as the prevailing conditions within the engine, for example the amount of exhaust gas recirculation (EGR) used, the rail pressure and injection timing.

NO_x mass flow quantities that have been observed for this report are samples, and may not generally reflect the situation on other cars, other driving situations or other ambient conditions.

The effect of SCR catalyst aging could not be measured on the tested car, as the tested car was purchased with the SCR catalyst aging factor already below the encoded switch value. As such, only the lowered threshold was used by the original software.

10 Defeat Device #3: Intake Air Temperature

10.1 Background

The ambient or intake air temperature should not significantly affect SCR operation. Nevertheless, it is used in the tested car as one criterion to switch to the alternative model. A temperature switch compares the intake air temperature with 12°C, and enforces a switch to the alternative model when the intake air temperature is below this threshold. A switch back to the load model is only allowed when the temperature then raises above 15°C (hysteresis).

When switched to the alternative model, either due to the intake air temperature or any other criteria, efficiency is further reduced.

10.2 Changes via Software Update

The mechanism was changed in the following aspects:

1. The mechanism of switching to the alternative model based on intake air temperature was removed completely.

11 Defeat Device #4: Restart Protection

11.1 Background

The heavy use of hysteresis means that during regular driving it is hard to make the SCR system re-enable the load model once the alternative model has been triggered by each individual defeat device.

In scenarios where the car stops and re-starts often (for example Taxi drivers), the hysteresis would not be effective as the hysteresis is reset when the engine stops. In such scenarios, the SCR system would continuously switch back to the load model. In the analyzed software, this is prevented even in such scenarios with a “restart protection”, as described below.

11.2 Details

An additional defeat device is present, which will observe the SCR temperature during the first 20 seconds. If it exceeds 50°C at any point, then for the next 240s the usage of the alternative model is enforced unless the total amount of NO_x emissions reaches 1800mg.

In practice, this means that if the car is stopped and re-started, the next 4 minutes will be forced to the alternative model.

The logic that implements this behavior is complex and can be configuration to involve additional criteria. For example, the total amount of NO_x emissions is tracked, and upon exceeding a pre-determined value, falling back into the ammonia load model is allowed if a minimum engine runtime time has been exceeded, which can depend on the ammonia stored in the SCR catalyst. Some of this additional logic is configured (using the calibration data) to have no effect on the analyzed vehicle.

11.3 Changes via Software Update

- This mechanism has been removed completely.

12 Defeat Device #5: SCR Temperature

12.1 Background

The exhaust gas heats up the SCR catalyst as it passes by. As such, the temperature of the SCR catalyst is directly depending on the heat flow volume of the exhaust. At higher speeds, with higher exhaust temperatures and higher mass flow rates, higher SCR temperatures can be expected. The SCR catalyst warms up from ambient temperature after the engine start. The SCR catalyst is cooled by the ambient air, so at colder ambient temperatures generally slightly lower SCR temperatures can be expected.

The diagram below shows typical observed SCR temperatures in normal driving conditions. After the engine start, the SCR catalyst slowly warms up from the exhaust gas until it reaches operating temperatures. Warmup can be accelerated by doing additional fuel injections to produce higher temperature exhaust gas.

During DPF (Diesel Particulate Filter) regenerations, high temperatures are required. These are achieved by heating up the exhaust gas with torque-neutral fuel injections. This also heats up the SCR catalyst (which sits further downstream), so high temperatures (up to 550°C typically) are reached during DPF regeneration. At such high temperatures, NO_x reduction via SCR is not feasible because any injected AdBlue would directly oxidize, eventually producing more NO_x. DPF events though are relatively rare (even few hundred kilometers, lasting a few minutes).

During normal driving, temperatures between 180°C and 350°C can be expected in the SCR catalyst.

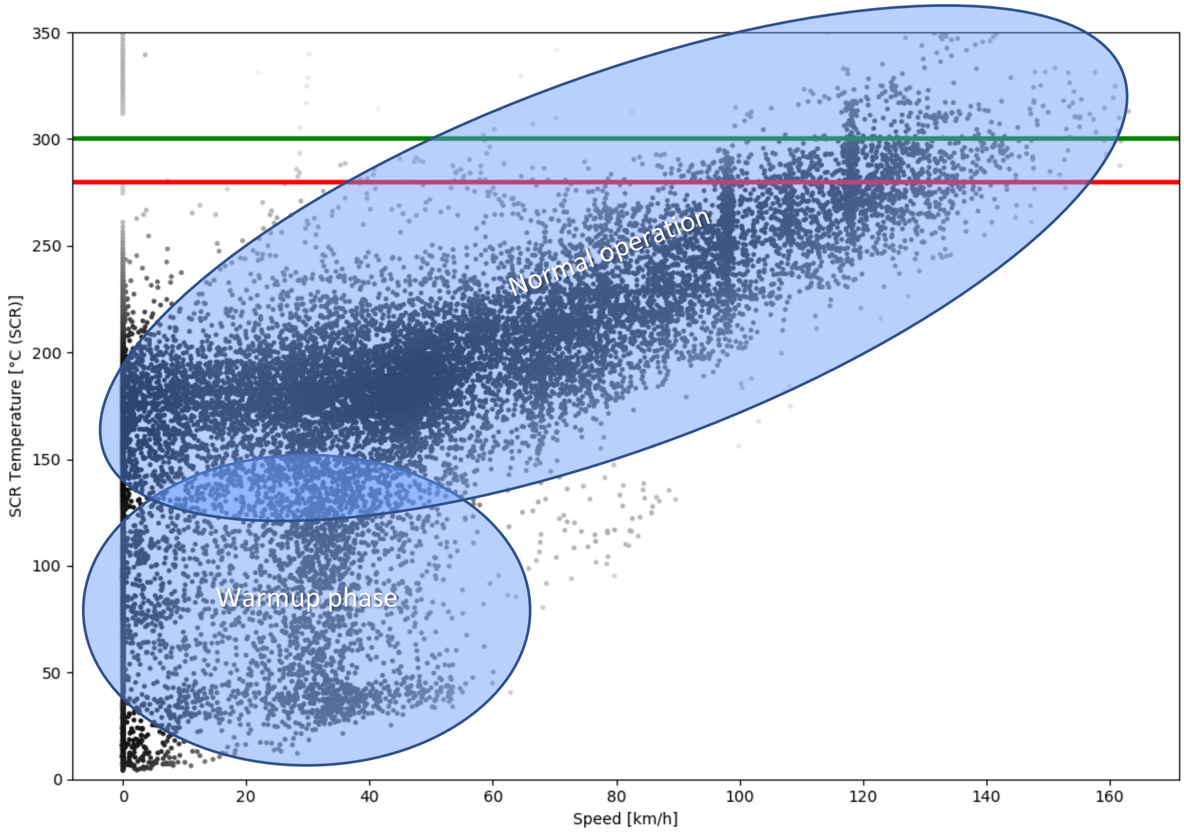

Figure 9 - SCR temperature during Real-World driving scenarios. High SCR temperatures are used in DPF regeneration events, low temperatures are after engine start (warmup). The green bar indicates the initial temperature threshold. If this temperature is exceeded, the alternative model is enforced until the red bar (hysteresis) is underrun.

12.2 Details

The ECU calculates a threshold as a function of the previously described "SCR catalyst aging" factor, as seen in the next figure.

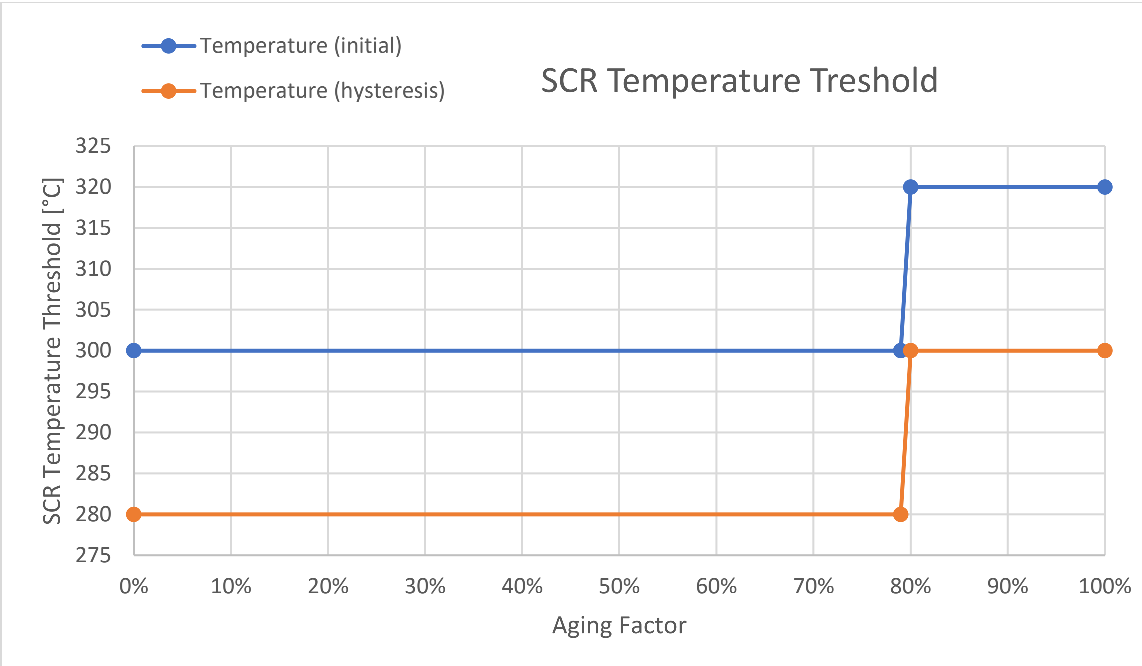

Figure 10- SCR temperature threshold as a function of Aging Factor, extracted from ECU calibration data. It can be seen that the SCR temperature threshold rapidly changes when the aging factor reaches a particular state (internally modelled as "80%").

The tested car has an internal aging factor of ca. 69%. This means that in normal operation, after giving the SCR sufficient time to warm up, at roughly 120 km/h the SCR catalyst temperature typically approaches 300°C, at which the SCR temperature defeat device will force a switch to the alternative model.

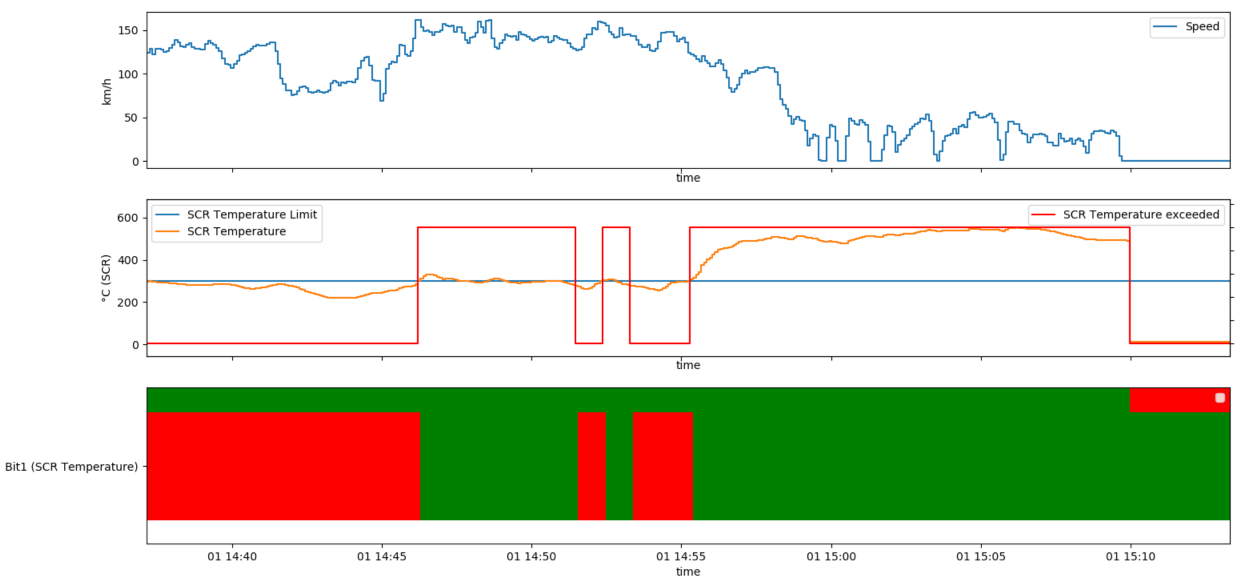

Figure 11 – Observed measurement data during an event where high SCR temperature (exceeding 300°C) enforces a switch to the Alternative Model. (Note that other Defeat Devices are activated at the same time, already enforcing the Alternative model). During the second half (starting around 14:47h) a DPF (Diesel Particulate Filter) regeneration event can be observed, yielding very high exhaust temperatures even though vhiecle speeds are moderate.

12.3 Changes to calibration data in software update

1. The threshold was changed from 320%/300°C to 275°C; there is no effect of SCR catalyst aging anymore.
2. The hysteresis was changed from 20K to 15K, so the lower threshold was changed from 280°C to 265°C.

12.4 Summary

Observing SCR temperature is critical for estimating the NO_x reduction efficiency. SCR operation is generally limited during temperatures that are above a threshold that is commonly exceeded during regular moderate-to-high-speed driving. The threshold was even lowered for the software update, indicating that there is a physical necessity of reducing SCR usage.

However, the updated software manages to keep the SCR efficiency between 70% and 90%, even though usage of the Ammonia Load Model is not possible in this case.

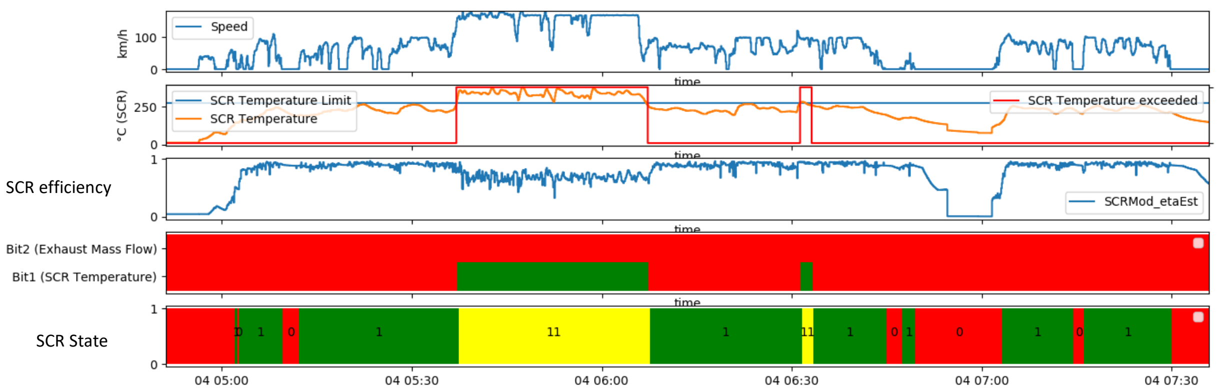

Figure 12 – Measurement data during event where high SCR temperature causes a switch to the alternative model in the updated software. SCR state: Red – dosing disabled, Green – Load model, Yellow – Alternative model. SCR efficiency, while reduced from when operating in the load model, is still maintained between 60%-80% when the alternative model is active.

12.5 Limitations of the Analysis

The SCR catalyst temperature is a result of the heat input from the exhaust gas into the catalyst. As such, it is correlated to the exhaust mass flow and temperature history. One major factor of these quantities is thereby vehicle speed, but many other factors exist as well. The displayed correlation between vehicle speed and SCR catalyst temperature thus should be seen as exemplary only and is not defining the SCR temperature. The SCR catalyst temperatures that have been observed for this report are samples, and may not generally reflect the situation on other cars, other driving situations or other ambient conditions.

The effect of SCR catalyst aging could not be measured on the tested car, as the tested car was purchased with the SCR catalyst aging factor already below the encoded switch value. As such, only the lowered threshold was used by the original software.

13 Defeat Device #6: AdBlue average consumption

13.1 Background

The amount of AdBlue consumption is directly proportional to the amount of ammonia that is made available for NO_x reduction. As such, the AdBlue average consumption is the result of the control mechanisms that regulate the dosing of AdBlue.

Excessive AdBlue dosing can be a symptom of a malfunction in the emission control system; it could thereby be argued that excessive AdBlue dosing should be prevented in itself to avoid over-dosing AdBlue during system malfunctions. However, monitoring the AdBlue usage for the purpose of detecting a malfunction is not a viable approach as it is a very slow indicator.

As such, AdBlue average consumption should not have an effect on the SCR efficiency calculations.

13.2 Details

The ECU tracks the average AdBlue consumption, and will enforce a switch to the alternative model when the AdBlue average consumption exceeds 820ml/1000km.

Additionally, once switched to the alternative model, the SCR target efficiency is reduced based on the average consumption (and the accumulated NO_x mass for the current driving cycle). The dominant factor is the average consumption – starting at ~800ml/1000km, the efficiency is reduced significantly, especially at higher consumption. This inherently cripples AdBlue consumption, regardless of the physical necessity of dosing larger amounts.

		Accumulated NO_x mass in this driving cycle					
		5.0g	6.0g	20.0g	30.0g	31.0g	35.0g
Average AdBlue consumption [mg/1000km]	400	100.0%	100.0%	110.0%	110.0%	120.0%	120.0%
	650	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
	800	95.0%	100.0%	100.0%	100.0%	95.0%	90.0%
	1000	70.0%	95.0%	95.0%	95.0%	70.0%	65.0%
	1200	40.0%	90.0%	90.0%	60.0%	40.0%	35.0%
	1400	17.0%	85.0%	22.0%	22.0%	17.0%	13.0%
	1600	8.0%	10.0%	10.0%	10.0%	8.0%	5.0%
	3000	3.0%	5.0%	5.0%	5.0%	3.0%	1.0%

Figure 13 - SCR efficiency correction based on AdBlue average consumption, extracted from calibration data of original software.

13.3 Changes via Software Update

This mechanism has been removed completely.

13.4 Limitations of the Analysis

Due to the abundance of defeat devices, it was surprisingly hard to drive the car in a way that sufficient AdBlue was being dosed to trip the AdBlue average consumption; the car operated in the Alternative Model in a large portion of time. As such, the physical effect of the AdBlue switch was only observed for very limited time. The effect of the SCR efficiency correction however could be seen in the observed data.

14 Defeat Device #7 (EGR): Engine Start temperature

14.1 Background

The engine temperature at engine start can be a useful quantity to control additional measures that will enhance engine behavior during startup.

However, once the engine has been warmed up, the behavior of the engine and the emission control system should no longer depend on the engine start temperature.

Similarly, the maximum engine temperature that was observed during a particular driving cycle should have no inherent effect on engine behavior.

14.2 Details

Another defeat device reduces the EGR rate depending on the maximum observed engine temperature during this driving cycle and the engine start temperature. In many cases, both of these values do not reflect any property of the current engine operation, but affect the EGR at all times.

This thermal window has been designed so that full EGR operation is only possible when the engine was started between 18°C and 35°C, and the engine temperature has never exceeded 86°C.

	Maximum engine temperature								
		0 °C	20 °C	40 °C	50 °C	60 °C	84 °C	86 °C	95 °C
Engine start temperature	-50 °C	0.0%	0.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
	17 °C	0.0%	0.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
	18 °C	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%	100.0%
	35 °C	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%	100.0%
	36 °C	0.0%	0.0%	0.0%	0.0%	100.0%	100.0%	100.0%	100.0%
	70 °C	0.0%	0.0%	0.0%	0.0%	100.0%	100.0%	100.0%	100.0%
	85 °C	0.0%	0.0%	0.0%	0.0%	100.0%	100.0%	100.0%	100.0%
	90 °C	0.0%	0.0%	0.0%	0.0%	100.0%	100.0%	100.0%	100.0%

Figure 14 – Relative EGR reduction depending on maximum engine temperature observed in this driving cycle and the engine start temperature, extracted from calibration data of original software. Marked in red are the operating conditions that can be expected in the NEDC testing.

14.3 Correlation to the NEDC test cycle

Noteworthy is that conditions are estimated to be true for the NEDC testing at all times, especially in the repeated ECE-15 part that only uses low engine power, but not satisfied during many regular driving cycles.

14.4 Changes via Software Update

While the logic has been retained in the software update, the map has now all-zero, meaning that no EGR reduction happens based on engine start temperature and maximum engine temperature.

15 Defeat Device #8 (EGR): "Hot & Idle"

A defeat device reduces the EGR when the engine is warmed up (>80...90°C) but idling. This scenario often happens when driving with moderate to high speeds (such as on a highway), and then continue through an urban environment. In this case, the EGR used for the later parts of the driving cycle would be reduced.

		Current engine temperature											
		-40 °C	-30 °C	0 °C	20 °C	40 °C	55 °C	75 °C	80 °C	90 °C	100 °C	103 °C	110 °C
rpm	800	100.0%	100.0%	50.0%	4.7%	2.1%	0.0%	0.0%	0.0%	80.0%	80.0%	100.0%	100.0%
	1000	100.0%	100.0%	50.0%	5.0%	1.9%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%
	1200	100.0%	100.0%	50.0%	5.0%	1.9%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%
	1400	100.0%	100.0%	50.0%	10.0%	3.7%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%
	1600	100.0%	100.0%	50.0%	10.0%	3.7%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%
	1800	100.0%	100.0%	50.0%	10.0%	3.7%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%
	2000	100.0%	100.0%	50.0%	15.0%	6.8%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%
	2200	100.0%	100.0%	60.0%	20.0%	10.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%
	2400	100.0%	100.0%	70.0%	20.0%	10.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%
	2800	100.0%	100.0%	70.0%	20.0%	10.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%
	3200	100.0%	100.0%	70.0%	20.0%	10.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%
	3600	100.0%	100.0%	70.0%	20.0%	10.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%

Figure 15 – Relative Reduction of EGR depending on current engine temperature and engine speed, extracted from calibration data of original software. Green areas indicate pure temperature-depending reduction, likely to prevent clogging of EGR. Red areas indicate a defeat device designed to reduce EGR when the engine has been running to operating temperature, and then idles.

15.1 Changes via Software Update

The software update retains the logic itself, but the map has been significantly changed. The operating range has been extended, so that EGR is not as much reduced in low (<35°C) temperatures, similar to improvements on the high-temperature side.

Most importantly, the entries that cause the engine to reduce EGR when idling have been removed.

		Current engine temperature											
		-30 °C	0 °C	20 °C	35 °C	55 °C	105 °C	107 °C	110 °C	121 °C	124 °C	132 °C	135 °C
	800	100.0%	45.0%	4.7%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%
	1000	100.0%	45.0%	5.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%
	1200	100.0%	45.0%	5.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%	100.0%
	1400	100.0%	45.0%	10.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%	100.0%	100.0%
	1800	100.0%	45.0%	10.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%	100.0%	100.0%
	2000	100.0%	40.0%	15.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%	100.0%	100.0%
rpm	2200	100.0%	35.0%	20.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%	100.0%	100.0%
	2400	100.0%	35.0%	20.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%	100.0%	100.0%	100.0%
	3000	100.0%	35.0%	20.0%	0.0%	0.0%	0.0%	0.0%	100.0%	100.0%	100.0%	100.0%	100.0%
	3500	100.0%	35.0%	20.0%	0.0%	0.0%	0.0%	0.0%	100.0%	100.0%	100.0%	100.0%	100.0%
	4000	100.0%	35.0%	20.0%	0.0%	0.0%	0.0%	0.0%	100.0%	100.0%	100.0%	100.0%	100.0%
	4500	100.0%	35.0%	20.0%	0.0%	0.0%	0.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

Figure 16 – Relative Reduction of EGR depending on current engine temperature and engine speed, extracted from calibration data of updated software. Green shows areas of improvement; the entries that reduce EGR in idle after usage have been removed completely. (Note the change of the temperature scale.)

16 Improvements for the updated version

16.1 Limitations of the analysis

To analyze the difference between the original software from 2016 with the updated software from end of 2019 a method was needed to switch between two software versions, but otherwise leave the operating conditions unchanged. This was done by first cloning the original engine ECU with a third-party tool onto a second ECU, and then applying the updated software to this ECU. This was done to preserve the integrity of the original ECU for further investigations.

After the installation of the updated ECU, no on-board diagnostic errors were flagged.

16.2 Details

The defeat devices present in the original software cripple SCR usage in regular operation. This can be quantified by observing the distribution of the target SCR efficiency. This has been plotted below – the X axis shows the observed efficiency ranges (0...1 for 0%...100%), the Y axis shows how often this efficiency range has been observed over time (unit-less). Higher bars indicate that these efficiency ranges have been observed more often. Compared with the updated software, low efficiency ranges (causing higher NO_x rates) are much more prevalent; there are almost no times where the engine operated with an SCR efficiency of > 80%.

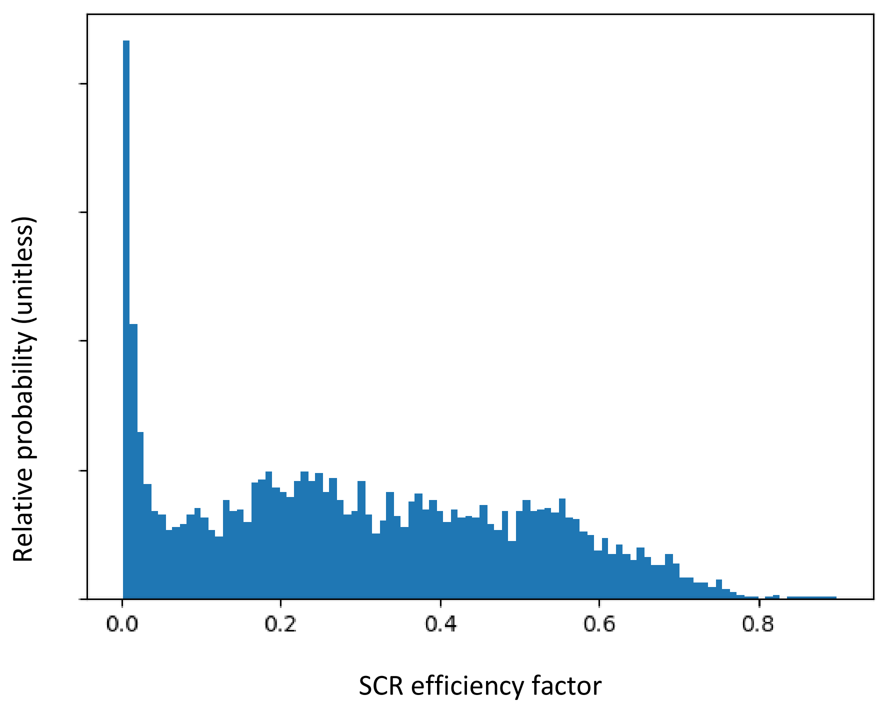

Figure 17 – Measurement data: Distribution of SCR efficiency with original software. Higher bars indicate higher relative probability of a specific SCR efficiency to occur in real-world driving.

The updated software shows a drastically different picture. While there are still occurrences of low SCR efficiencies, most of the time the engine operates between 80% and the upper 90%-range.

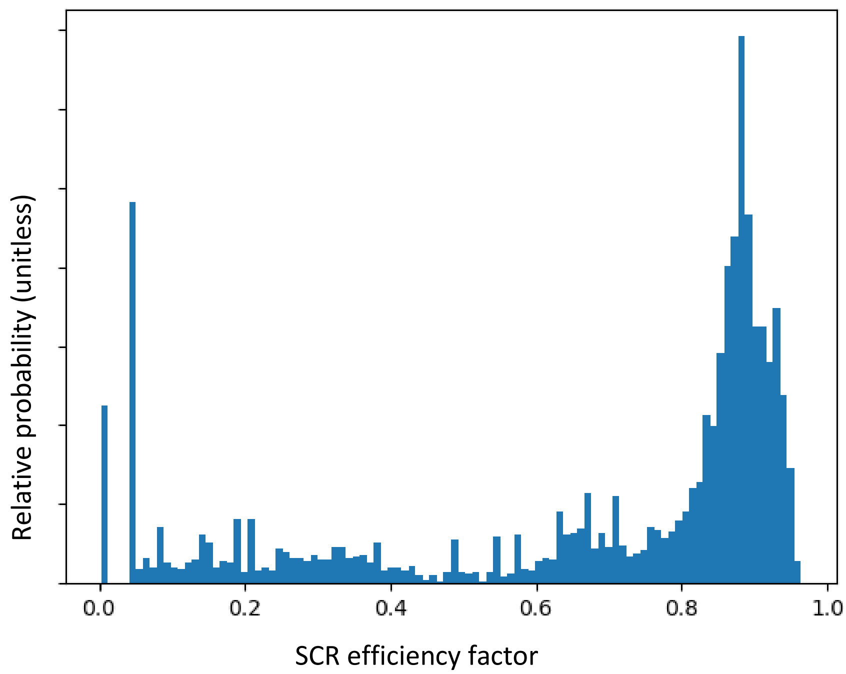

Figure 18 – Measurement data, distribution of SCR efficiency with updated software. Higher bars indicate higher relative probability of a specific SCR efficiency to occur in real-world driving.

16.3 Effect on AdBlue consumption

The increased efficiency comes, however, with the cost of increased AdBlue consumption. The average AdBlue consumption with the old software was determined as 0.75l/1000km, with the updated software, much higher values of 1.61l/1000km (>2X) are observed.

16.4 Limitations on the analysis

By the nature of doing data collection in typical usage, the driving cycles that have been observed with the original software do not match these from the updated software completely. Although the same driving style and pattern has been employed, no systematic testing of specific driving conditions has been attempted. As such, care must be taken when comparing the pre-update and post-update values.

However, it is believed, based on the observation of the software changes, the observed effect on AdBlue dosing, that these values are representative of long-time usage, and thus can be compared.

16.4.1 Summary

In summary, the following changes to the defeat devices have been found in the updated software:

16.4.2 SCR:

- SCR Temperature limit was removed, SCR aging dependency was removed, effective limit changed from 300°C to 275°C.
- Exhaust mass flow limit was removed as switch condition completely, efficiency correction map was improved to allow operation in alternative mode while maintaining high SCR efficiency
- NO_x mass flow limit was removed as switch condition, removed efficiency correction in alternative model based on NO_x mass flow.
- Air temperature dependency was removed.

- ”Restart-Protection” was removed.
- Both the switch as well as efficiency correction based on AdBlue consumption were removed.

16.4.3 EGR:

- EGR reduction based on engine start and maximum temperature was removed.
- EGR reduction when engine is hot and idling has been removed; EGR is still limited at very high and low temperatures, but no longer special-cases idling.

In summary, all defeat devices that have been identified have been removed in the updated software.

17 Conclusions

The general observation in the test vehicle is that the target efficiency of the SCR and EGR systems are intentionally de-rated based on factors that are not based on physical necessities but rather on the manufacturer’s policies.

This research identified the use of 8 defeat devices, of which six are related to the SCR system and two to the EGR system. Three of the SCR-related devices are dependent on an “aging factor”. This factor causes two of these devices (numbers 1 and 2, exhaust gas mass flow and NO_x mass flow) to be activated at an aging ratio of 1%, i.e. very early in the lifetime of the vehicle, and a third (number 5, SCR temperature) at 20%. The majority of the lifetime of a vehicle hence the SCR-related defeat devices are active.

For the SCR system, the defeat devices have the following in common:

- They trigger on physical properties that are generally needed to be monitored for extreme conditions, such as temperature, mass flow etc.
- However, they trigger routinely in what can be considered as normal, “real world” driving conditions.
- They are designed to have an effect well after being “triggered”, for example by using a large hysteresis and/or employing a “restart protection”.
- They greatly reduce the internal efficiency estimation of the SCR system, which drastically reduces AdBlue dosing, which in turn generates a much higher NO_x output.

In relation to the EGR system, a thermal window was identified, as well as a defeat device that reduces the EGR when the engine has been warmed up but is idling.

Due to the abundance of defeat devices, the car operated in the Alternative Model during most of the driving, employing a moderate driving style.

For some of the defeat devices, it is clear that they not triggered during NEDC test circumstance because the limits are clearly specified in the testing regulations, or because the aging factor that triggers their increased operation has likely not been reached at the moment of testing. For other defeat devices, it is the expectation that these are not triggered based on the predictions from regular car usage.

The updated software uses optimized thresholds that produce a much-improved NO_x performance, but does not require any other hardware changes. Each of the defeat devices that have been identified has been removed in the updated software, resulting in significant improvements of the system’s overall performance.

This improved efficiency, however, comes at the cost of a significant increase of AdBlue usage, of more than two times the initial value. Whether there are any other side effects associated with the software update is beyond the scope of this investigation.