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CATCHING DEFEAT DEVICES

HOW SYSTEMATIC VEHICLE TESTING CAN DETERMINE THE PRESENCE OF SUSPICIOUS EMISSIONS CONTROL STRATEGIES

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ACRONYMS AND ABBREVIATIONS

AC	Air Conditioning
AdBlue®	Aqueous urea solution used in diesel exhaust aftertreatment
AECD	Auxiliary Emissions Control Device
AES	Auxiliary Emissions Strategy
AWD	All-Wheel Drive
CARB	California Air Resources Board
CF	Conformity Factor, ratio to the laboratory type-approval emission limit
CO_2	Carbon dioxide
CVS	Constant Volume Sampling
DOC	Diesel Oxidation Catalyst
DPF	Diesel Particulate Filter
ECE	ECE-15 or UDC urban driving part of the NEDC
ECU	Electronic Control Unit
EGR	Exhaust Gas Recirculation
EPA	U.S. Environmental Protection Agency
EU	European Union
EUDC	Extra Urban Driving Cycle
FTP	Federal Test Procedure
FWD	Front Wheel Drive
GPS	Global Positioning System
KBA	Kraftfahrt-Bundesamt, the German Federal Motor Transport Authority
HDV	Heavy-Duty Vehicle
LNT	Lean NO_x Trap
NEDC	New European Driving Cycle, used for laboratory type-approval testing
NO_x	Nitrogen monoxide (NO) and dioxide (NO_2)
NVH	Noise, Vibration, Harshness
O_2	Oxygen molecule
OBD	On-Board Diagnostic
PEMS	Portable Emissions Measurement System
RDE	Real-Driving Emissions, on-road type-approval procedure
TNO	The Netherlands Organisation for Applied Scientific Research
PM/PN	Particulate mass / particulate number
QA/QC	Quality Assurance and Quality Control
SCR	Selective Catalytic Reduction
VW	Volkswagen
WLTC	Worldwide harmonized Light vehicles Test Cycle, used for laboratory type-approval testing from September 2017 for new types of vehicles

EXECUTIVE SUMMARY

Nitrogen oxide (NO_x) emissions from diesel vehicles are a major contributor to air pollution, despite regulatory limits in place. In Europe, we estimate that about 6,800 deaths due to excess NO_x from cars and vans only could be avoided every year if on-road diesel vehicles performed in the real world within the limits defined in vehicle emissions regulation (Anenberg et al., 2017).

The Dieselgate scandal dramatically raised awareness of defeat devices, which are software calibrations that deactivate emission controls in the real world. Vehicles are certified on standardized tests, so deactivating the controls under other conditions can lead to orders-of-magnitude increases in emissions. In the United States, Dieselgate was very much about one individual manufacturer, Volkswagen, being caught using an illegal defeat device. In the European Union, the implications are much broader: in the aftermath of Dieselgate it became clear that most, if not all, diesel car manufacturers in the European Union were employing some type of defeat device. The member state type-approval authorities did not have any real experience in proving the existence of a defeat device, and defeat devices that would be illegal in the United States were not necessarily considered illegal in the European Union.

There are some conditions under which emissions controls need to be deactivated to protect the engine or aftertreatment system from damage. Defeat-device regulations provide for this. Unfortunately, in Europe the provision is being used to justify unnecessary deactivation of emissions controls, such as calibration changes based on ambient temperature, engine temperature at startup, and timers. In the United States, regulatory agencies have issued numerous guidance letters and additional rulemaking to define the boundary between proper and improper deactivation of emissions controls. Such guidance does not exist in Europe, and European regulators thus have generally not questioned manufacturers' claims.

To help government agencies and third parties determine the presence of an inappropriate calibration change, this report develops, details, and illustrates through an actual example a seven-step methodology for finding defeat devices through vehicle testing. The steps, which are demonstrated on Mercedes-Benz C-Class Euro 6b vehicles, are shown in Figure ES1 and detailed as follows:

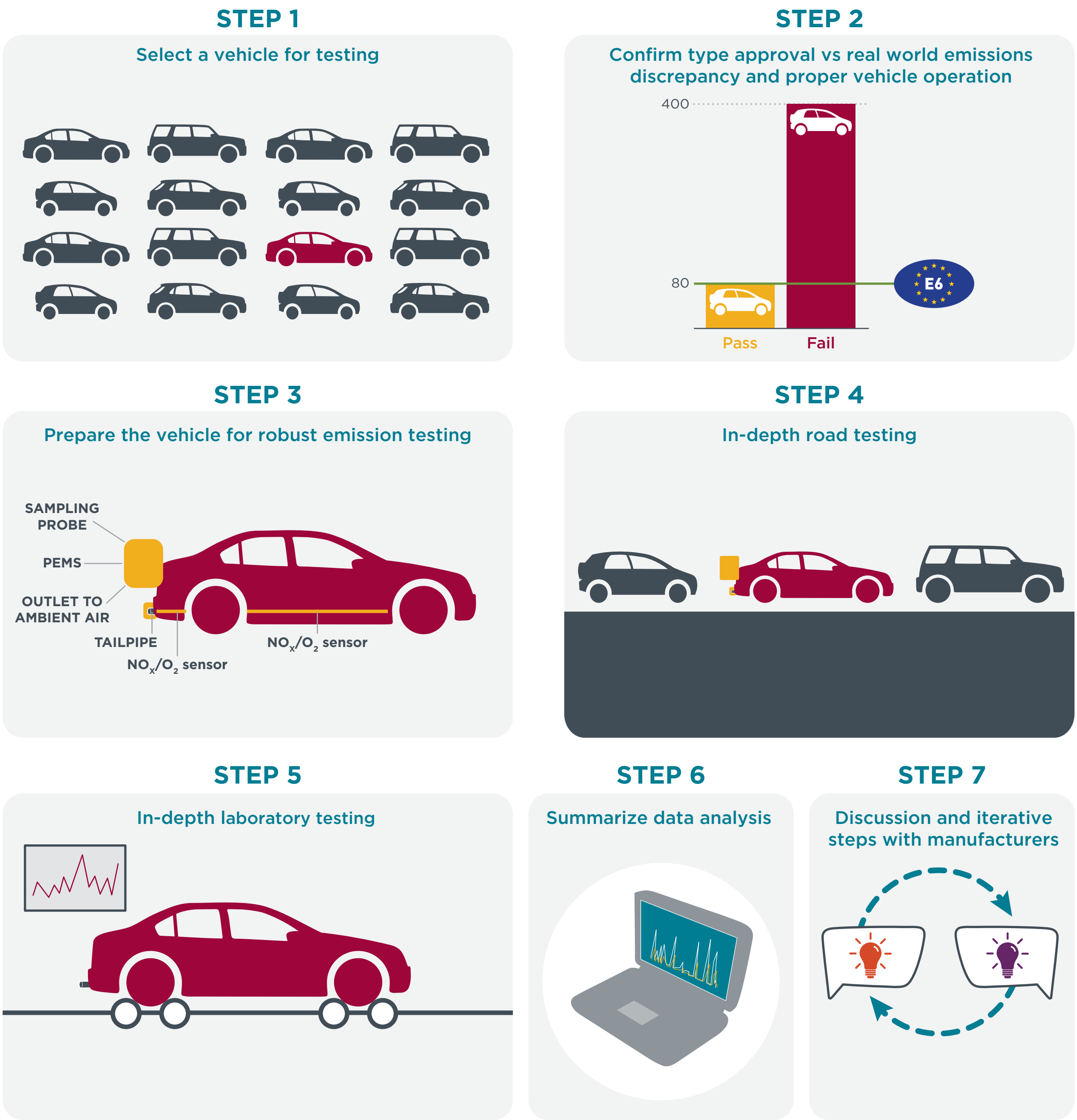


Figure ES1. The seven steps of the testing protocol for detecting defeat devices.

Step 1: Select a vehicle for testing. Since defeat-device testing is time-consuming and resource-intensive, programs to pre-screen the fleet should be put in place. There are two good ways to screen vehicles: remote sensing and gathering data from government and third-party testing. Pre-screening greatly increases the likelihood of selecting a vehicle with a defeat device.

Step 2: Perform preliminary type-approval and real-world driving testing, using simple screening sensors. A properly operating vehicle with a defeat device will meet type-approval limits under official test conditions and will exhibit higher emissions in real-world driving. It can save a lot of time and expense to confirm these trends prior to any in-depth testing on a given vehicle.

Step 3: Prepare and instrument the vehicle for robust emissions testing and investigation. It is important to measure enough testing parameters to allow investigation into the causes of any observed high emissions. For example, we measured both engine-out as well as tailpipe emissions to differentiate between the behavior of the exhaust gas recirculation (EGR) and selective catalytic reduction (SCR) emissions control. This allows the possibility of determining the conditions in which different EGR or SCR calibration strategies are employed. To the extent possible, the instrumentation of the vehicle should be kept independent of vehicle systems such as the electronic control unit (ECU) to avoid triggering defeat devices, or a sensitivity test should be made without such instrumentation to see whether emissions change. To facilitate use of far cheaper sensors that still yield reasonably reliable results, the ICCT has helped develop methods to:

a. estimate carbon dioxide (CO_2) concentration from the oxygen (O_2) concentration measured by a NO_x/O_2 concentration sensor (Appendix B);

b. estimate EGR rate using engine air flow rate and temperature parameters (Appendix C); and

c. estimate NO_x g/km using average NO_x concentration from sensors, plus an estimate of the CO_2 concentration and fuel consumption (Appendix D).

Step 4: Road testing. Assuming that Step 2 confirms high real-world emissions and low type-approval emissions, the next question is what is causing the change? Changes can best be identified step-by-step by (a) mimicking the laboratory conditions on the road and (b) mimicking the road conditions in the lab. It is also beneficial to keep the test protocol flexible. If you see something strange, add tests and investigate. Step 4 addresses the road-testing component of this strategy by digging deeper into the real-world emissions behavior of a potential defeat device using portable emissions measurement system (PEMS) tests. Practically, this can be done either by starting with normal real-world driving and gradually moving to Real Driving Emission (RDE) conditions and then driving that is more in line with official test conditions such as ambient temperature, preconditioning, and test cycle; or the reverse. Changing a small number of variables at a time, or ideally just one, is the best way to narrow down the cause and find the trigger for a defeat device, keeping in mind that one vehicle could have multiple defeat devices and multiple triggers. Changes in emissions behavior should be repeatable and logically explainable. Where they are not, that is an indication of the presence of a defeat device.

Step 5: Laboratory testing. If high emissions or step changes in emissions are observed in Step 4, laboratory testing should be conducted to identify the defeat device trigger. It is recommended to start with official test conditions and gradually move to testing that is more in line with real-world driving conditions. Again, changing a small number of variables or ideally one variable at a time is the best way to narrow down the cause and find the trigger for a defeat device, keeping in mind that one vehicle could have multiple defeat devices and triggers. Unusual behavior that cannot be explained logically should be explored through additional testing.

Step 6: Summarize data analyses. After testing is complete, it is important to analyze and summarize the results. To look for defeat device triggers, it can be helpful to plot data in a form that would display whether well-understood emissions control functionality is present. For example, it is well known that SCR efficiency has a strong dependency on catalyst temperature, and data can be plotted to see whether a vehicle's emissions controls follow well-known trends.

Step 7: Discussion and iterative interactions with manufacturers by official agencies. After government authorities finish collecting and analyzing test data, the next step is to approach the manufacturer for additional information and responses addressing suspicions. Third parties lack the authority to compel manufacturers to respond to questions and provide additional information, so we did not perform this step.

Multiple suspected defeat devices were found in the Mercedes C-Class vehicles that we tested. Likely defeat devices identified by the testing protocols were changes in EGR rate and SCR efficiency based on ambient temperature, EGR rate changes based on some measure of engine temperature, and reductions in SCR efficiency possibly based on some sort of timer or accumulated urea consumption. There were also possible defeat devices linked to the length of the test and preconditioning before the test. Finally, we found strategies that limited the EGR flow rate outside engine conditions found on the NEDC, possibly due to system design limitations. As can be seen in Figure ES2, when several of these defeat devices and design limitations are combined, we observed NO_x emissions of as much as 20 times the type-approval limit.

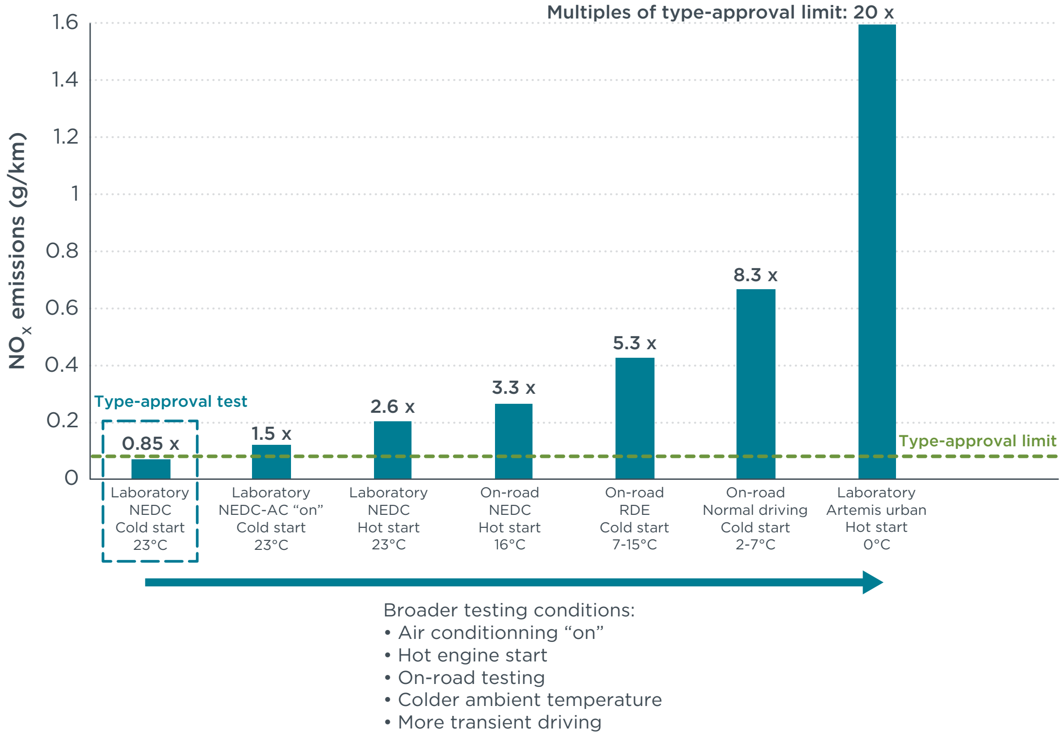


Figure ES2. NO_x emissions for the Mercedes C-Class Euro 6b diesel, tested over a number of driving conditions in which parameters such as ambient temperature, engine temperature, and driving cycle were varied.

INTRODUCTION

Nitrogen oxide (NO_x) emissions from diesel vehicles are a major contributor to air pollution, despite regulatory limits in place. In Europe, we estimate that about 6,800 deaths due to excess NO_x from cars and vans could be avoided every year if on-road diesel vehicles performed in the real world within the limits defined in vehicle emissions regulation (Anenberg et al., 2017).

While the U.S. Environmental Protection Agency (EPA) and the California Air Resources Board (CARB) have a long history of enforcing defeat-device provisions, the Volkswagen scandal dramatically increased awareness of defeat devices and highlighted the lack of enforcement outside the United States. In Europe, member states have conducted testing and found very high in-use emissions but have struggled to prove illegal defeat devices. Contrast this to the United States, where VW has had to pay more than $25 billion in fines and remedies, and enforcement action is also being taken against Fiat Chrysler Automobiles (FCA). The EPA and CARB have also started doing un-prescribed real-world testing. Their exact methodology has not been made public to keep manufacturers from knowing how their vehicles will be evaluated.

WHAT IS A DEFEAT DEVICE?

A defeat device is any calibration change that increases emissions under conditions normally encountered in-use, unless the calibration change is required for cold starts, safety, or to prevent damage to the engine or emissions aftertreatment system. This definition is consistent in both the United States and in Europe (Muncrief, German, & Schultz, 2016). Some examples of allowable calibration changes are:

- Cold starts of gasoline vehicles at low ambient temperatures, below about 5°C, as gasoline does not evaporate well at colder temperatures and additional fuel is needed for stable operation.
- The aftertreatment system needs to reach a minimal temperature to reduce pollutants after any cold start, regardless of ambient temperature. In these conditions, a fast catalyst warm-up is often needed during the first couple of minutes after start that consists of delaying spark or injection timing and increasing idling speed, which increases fuel consumption.
- Extended operation at high loads may cause excessive catalyst temperatures and damage the catalyst—although even here the catalyst temperature must be modeled or measured, and the calibrations changed only when the damage threshold is reached.
- Regeneration events, such as when burning particulate matter stored in a diesel particulate filter, or to remove sulfur stored on a lean-NO_x trap.

The key is that these calibration changes should be limited and should not lead to overall high emissions in real-world driving. Real-world emissions will always be somewhat different from emissions on laboratory test cycles because of differences in ambient conditions and driving behavior. Defeat devices cause unnecessary step changes in control behavior and emissions.

IF THE U.S. AND EU REGULATIONS ARE SIMILAR, WHY IS ENFORCEMENT SO DIFFERENT?

Enforcement problems in the European Union center on the defeat-device exemption for potential damage to the engine or emissions aftertreatment system. In the United States, in addition to addressing Auxiliary Emissions Control Devices (AECDs) and defeat devices in three sections of the regulations, EPA has issued six guidance documents defining acceptable calibration changes to protect the engine and aftertreatment.[1] Advisory Circular 24-3 includes a section barring calibration changes that are needed only because of the use of inferior hardware. Similar guidance and prohibition of inferior hardware do not exist in the European Union. Thus, regulatory agencies in Europe have little expertise to evaluate manufacturer claims of potential engine or aftertreatment damage and usually accept such claims without question.

Manufacturers have made a number of arguments to justify calibration changes in the European Union that are not allowed in the United States (German, 2016a; German, 2016b). For example:

- **Timer-related** calibration changes are frequently asserted as needed to prevent component "heat-up" over time. However, for a properly designed emissions control system using state-of-the-art components, a heat-up strategy is necessary only at sustained, high engine loads. Thus, a timer-related defeat device is not needed except possibly at extreme driving conditions far beyond the boundaries defined in the RDE regulation.
- **Hot-start** alternative calibration strategies and high emissions are frequently justified with the assertion that starting the engine when it is still hot is a poorly defined state of the vehicle, where the temperature and buffering of the catalyst and other emissions control components are not well known. However, while it is not automatic to have better emissions performance immediately after a hot start, especially if the catalyst cooled down a bit, emissions should rapidly return to low levels. This is not the case after a cold start, where the time it takes for the engine and catalyst to reach normal operating conditions is the primary contributor to high emissions. Thus, in theory, emissions after a hot start should be much lower than after a cold start. In fact, this is what we find in the United States, where diesel hot-start emissions—defined as the 505-second drive cycle after a 10-minute soak—are on average only 15% of emissions after a cold start—using the same 505-second drive cycle after a cold start at around 24°C (see Figure 1). Yes, temperature and buffering of catalysts and other elements are not well known after a hot start, but the emissions impact of a cold start is so large that any uncertainty immediately after a hot start should have a relatively small impact on emissions.

1 Three regulations, the 40 CFR § 86.1803-01 (U.S. Environmental Protection Agency, 2016), the 40 CFR § 86.1809-12 (U.S. Environmental Protection Agency, 2014), the 40 CFR 86.1844-01 (U.S. Environmental Protection Agency, 2013), and three advisory circulars 24, 24-2, 24-3 (U.S. Environmental Protection Agency, 2001).

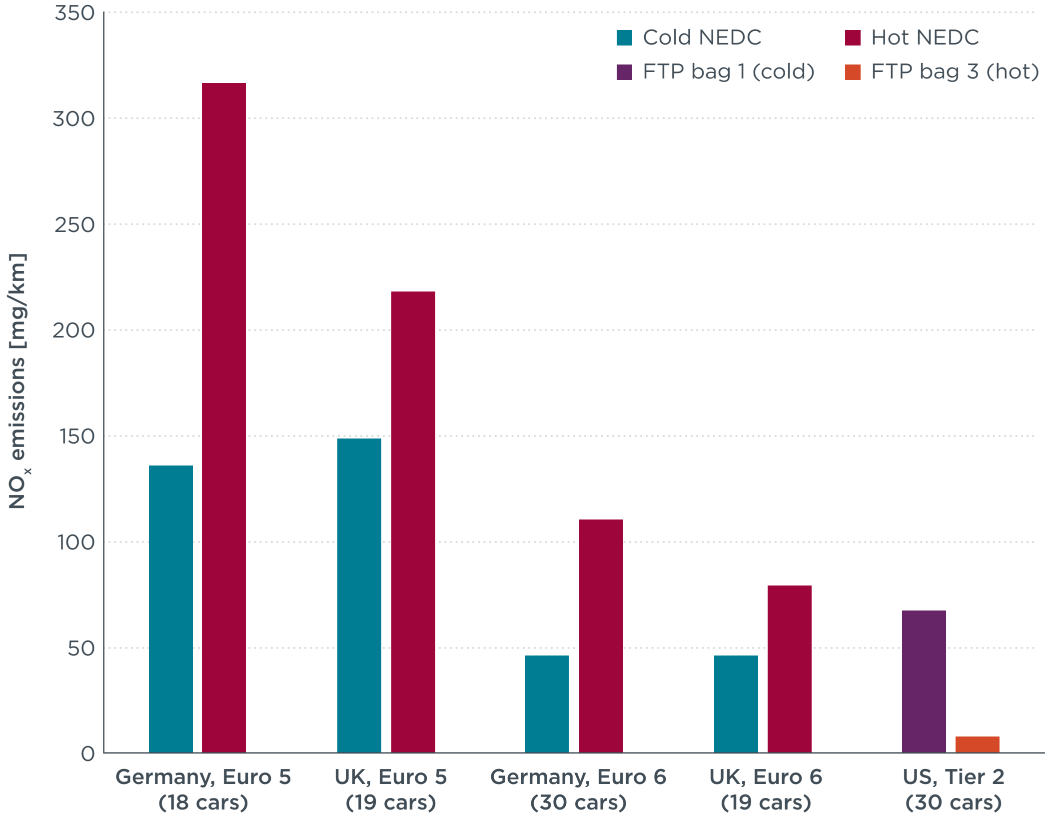


Figure 1: Diesel vehicle NO_x emissions from cold-start and hot-restart tests by Germany and the U.K., compared with similar test data from U.S. EPA.

- **Ambient temperature** is used by almost all manufacturers in Europe to justify turning off or reducing EGR to prevent condensation at colder temperatures. Similarly, reductions in both EGR and aftertreatment effectiveness at high ambient temperatures are justified as necessary to prevent damage due to high temperatures. However, condensation is actually a function of intake manifold temperature. While ambient temperature is one of the primary determinants, intake manifold temperature is also strongly affected by engine temperature, prior engine operation, intake air flow, and the temperature of the exhaust gases being recirculated. These factors should be used to model intake manifold temperature, reducing EGR only when absolutely necessary, instead of simply using ambient temperature. Similarly, any potential high-temperature damage is strongly affected by engine load and prior engine operation, not just ambient temperature.
- **Lack of preconditioning** is used to justify lower efficiency for SCR and lean NO_x trap (LNT) in real-world driving. It is true that SCR and LNT systems have some buffering, which is always in a well-defined state after the preconditioning required before the official laboratory tests. In the real world, an SCR system may not have sufficient stored ammonia or an LNT may not be empty when the test is started. However, if sufficient ammonia is not stored in the SCR, the ECU should be able to quickly detect this and add ammonia to compensate. Similarly, NO_x traps are regenerated every minute or so, so the preconditioning effect can affect emissions only during the first minute. Both of these effects are minor and should not have a significant influence on average emissions of real-world testing that lasts at least 30 minutes.

The European Union did not provide guidance on how to identify an illegal defeat device before 2017 (European Commission, 2017c), and European regulators have been unduly influenced by manufacturers' arguments. These types of arguments are used only in

Europe and are not accepted in the United States because they are needed only for poorly calibrated systems or systems that use inferior components (German, 2017). Thus, part of the purpose of this paper is to help regulators identify illegal defeat devices and document the conditions under which they are triggered.

WHY WOULD MANUFACTURERS USE A DEFEAT DEVICE?

Defeat devices are primarily a concern with diesel vehicles, where deactivating emissions controls in the real world can lower cost, improve fuel economy, extend urea refill intervals, reduce engine noise, improve performance feel, and shorten development time. Diesel engine combustion uses compression ignition and operates with excess oxygen in the air/fuel mixture. This excess oxygen results in very low engine-out hydrocarbon (HC) and carbon monoxide (CO) emissions and reduces fuel consumption and CO_2 emissions. However, ignition is controlled by the timing of the fuel injection, and the fuel ignites shortly after injection, resulting in high particulate emissions. Also, the excess oxygen precludes reduction of NO_x in a conventional three-way catalyst as is used for gasoline vehicles. Diesel engine-out NO_x emissions can be reduced by dedicated hardware that recirculates exhaust gas back to the combustion chamber, or EGR. SCR and LNT have been developed to reduce tailpipe NO_x emissions, but both are far more expensive than the three-way catalyst. There are also tradeoffs between NO_x and generation of particulate emissions in the engine. Thus, using defeat devices in a diesel engine can provide the following possible benefits:

» For a 2.0 liter car, a complete LNT system would cost roughly $360, and an SCR system, $800.[2] Installation of an inferior system can save hundreds of dollars per vehicle and still work properly during laboratory testing.

» The particulate trap costs roughly $240. Calibrating the engine for high NO_x emissions can reduce particulate emissions. Lower particulate emissions means the particulate filter would require fewer periodic regenerations, which in turn would allow for the use of a cheaper, less durable filter and could reduce fuel consumption.

» There is a tradeoff in fuel efficiency and NO_x emissions from the engine—calibrating for higher engine-out NO_x emissions can improve fuel economy by 2%–5%.

» LNT-equipped vehicles have to periodically inject extra fuel into the exhaust to reduce the NO_x stored on the LNT. Turning off or modulating this LNT regeneration process can also improve fuel economy by 2%–5%.

» SCR systems use ammonia as the reactant to reduce NO_x in the SCR catalyst. This is typically stored onboard the vehicle in the form of a urea solution, otherwise known as Diesel Exhaust Fluid or AdBlue®, which must be periodically refilled. Turning off the SCR system extends urea tank refill intervals for improved consumer acceptance, or it can be used to reduce urea tank size if the vehicle cannot accommodate a larger tank.

» There are also NO_x emissions and engine noise trade-offs. Diesel engines used to be notorious for their crackling sound, which was reduced in modern engines by injecting the fuel sequentially rather than all at once. This requirement to limit the noise from combustion plays an important role in defining injection strategies that balance additional cost against lower NO_x emissions, such as single or dual pilot injection, split injection, etc.

» The pursuit of a "fun to drive" vehicle encourages manufacturers to guarantee high performance drivability. By turning off EGR, more excess oxygen is available, more

2 Cost calculated using the methodology in the ICCT's 2012 emissions cost report with updated 2018 platinum group metal prices and production-cost reductions on some key components, such as the DPF substrate (Sánchez, Bandivadekar, and German, 2012).

fuel can be burned immediately if necessary, and the responsiveness to sudden load demand is greatly improved.

» Proper calibration is difficult and time-consuming. The use of defeat devices allows calibration engineers to save time and focus on other priorities, such as fuel-economy improvement which—unlike air pollutant emissions performance—can be perceived by the user of a vehicle.

There is relatively little incentive for gasoline engines to use defeat devices. Particulate emissions are usually very low, although gasoline direct fuel injection systems can create high particulate number emissions under some conditions. The three-way catalyst, combined with extremely precise air/fuel control, has proven to be remarkably effective and durable. Further, there is little tradeoff with drivability or fuel economy, and the exhaust control system is relatively cheap. Thus, while a few gasoline vehicles with high real-world emissions have been observed,[3] they are comparatively rare.

WHY IS ENFORCEMENT SO COMPLICATED?

Defeat devices are generally easy to design and difficult to detect. Defeat devices are, nowadays, embedded in proprietary computer code that is very difficult to access and interpret by third parties.[4] However, from September 1, 2020 onward, a new EU type-approval framework will grant type-approval authorities and technical services access to vehicle software (Mock, 2018). But even if you did scrutinize the computer code, there is not a single defeat device; vehicles with defeat devices usually have multiple calibration strategies. It is also very difficult to differentiate between normal calibrations designed to handle a wide variety of operating conditions and abnormal defeat device calibrations, and one would not know the emissions impact.

Meanwhile, hacking into the software and finding the actual code of the defeat device can be and has been done by some experts in the field. For example, the Ruhr University Bochum (RUB) and Felix Domke helped discover how Volkswagen and Fiat did it (Contag et al., 2017). That being said, modern ECUs can have hundreds of thousands of lines of code, and it requires either very advanced computer hacking skills or a huge amount of time and patience to have any chance of finding the relevant code. The work can be facilitated if the software architecture of the ECU is available, but that is rarely the case. There is no guarantee of success, and a very small number of experts have the skill set. Even in the case where Domke successfully found the relevant code in the VW software, he knew in advance that he was looking for a defeat device based on the distance values versus time associated with NEDC laboratory testing. Finding defeat devices in the code when you do not know in advance what you are looking for is far more difficult and, even if suspicious calibrations are found, the impact on vehicle emissions is not known. There is also a potential legal risk since the code can contain embedded intellectual property.

So, the starting point for enforcement is almost always data showing high real-world emissions. But as we have seen in Europe, manufacturers respond by giving engineering explanations for high emissions, asserting that they are the normal difference between laboratory and road-testing results or that the effectiveness of the emissions controls must be reduced under certain circumstances to protect the equipment. Without equal expertise in engines and emissions control systems, it is difficult for regulators to contest manufacturers' claims. The problem in Europe is compounded by the lack of robust published guidance on how to interpret the defeat-device regulation.

3 U.K. market surveillance report found track and real-world NO_x emissions more than eight times higher than the NEDC cold test limit on a gasoline Nissan Qashqai and more than four times the NEDC test limit on a gasoline Ford Fiesta (U.K. Department for Transport, 2018).

4 This is highly desirable, as tampering with ECUs is a serious problem that can disable emission controls.

The purpose of this paper is to build upon what we have learned from Dieselgate and provide guidance on how to test for the presence of defeat devices and build a strong evidence base. If there is a high risk of getting caught and paying the price, the appeal of using illegal defeat devices goes down. The focus of this paper is on defeat devices that manipulate NO_x emissions from diesel light-duty vehicles. Diesel NO_x is special, as it is more difficult to control; the control systems are expensive; and there are tradeoffs with fuel consumption and other attributes. However, the methodologies presented here would also work for other pollutants and vehicle types. This guidance is primarily intended for governments or type-approval authorities in the European Union as part of market surveillance activities, but it is equally applicable to third parties.

While quality assurance and quality control (QA/QC) are not covered in detail in this paper, it is also important that the best QA/QC for testing is followed during any testing program, such as documentation and calibration of analytical equipment.

EXAMPLES OF KNOWN OR SUSPECTED DEFEAT DEVICES

We have evidence of several defeat devices that have been used in diesel cars. We can group these into three categories. It is also important to note that some defeat devices are "hard switch" strategies, but a "switch" is not the only type of defeat device and is not any worse than the others.

CATEGORY 1: SENSING THE VEHICLE IS BEING DRIVEN OVER A SPECIFIC DRIVING CYCLE

This was the strategy used by VW to deactivate emissions controls. As shown by Domke and researchers from RUB, VW tracked cumulative distance versus cumulative time and compared the second-by-second results with that of the laboratory test cycles (Contag et al., 2017).

CATEGORY 2: SENSING THE VEHICLE IS UNDERGOING A CHASSIS DYNAMOMETER TEST

As VW was proposing various solutions during the U.S. investigation into VW defeat devices, VW added a defeat device that was activated by the steering wheel position (Domke, 2016). During laboratory testing, vehicles are tied down and the front wheels do not turn side to side.

In 2017, the Porsche and Audi subsidiaries of the VW group were accused of using a vehicle's tilt and altitude variation to change emissions strategies. *Der Spiegel* magazine and experts from TÜV Nord conducted intensive research to prove that a small change of the usual testing conditions on the dynamometer—by inserting a piece of wood under the stationary wheels that are not driven on the dynamometer to incline the vehicle—would lead to exceeding the NO_x limit by 68% (Schmitt, 2017).

There are additional ways to detect whether a vehicle is being tested on a dynamometer. For example, typically only the drive wheels turn during the dynamometer test, so manufacturers could program vehicles to look for differences in rotational speed between the front and rear wheels, which can be done by reading sensor data from antilock braking systems.[5] It is often even necessary to put the vehicle in its intended "dyno" mode state—for example by pushing a combination of buttons on the steering wheel in a given sequence—to enable the vehicle to be tested without triggering safety systems.[6] Dynamometer tests are run at a prescribed ambient temperature and with an engine that has been cooled down to match the ambient temperature. The computer can look for this combination and change calibrations under any other conditions. GPS units know where the vehicle is located and could change calibrations if engine rotational speed is above idle speed but the vehicle location is not changing.

CATEGORY 3: SENSING THE VEHICLE IS WITHIN THE CONDITIONS OF A TYPE-APPROVAL TEST

This is by far the most common defeat device, most likely because manufacturers using these strategies in Europe consistently assert that the calibration changes are necessary for drivability or to prevent damage to the engine or emissions control system. As

5 This specific method does not work on 4-wheel-drive chassis dynamometers, which are becoming more common.

6 The safety systems are triggered by sensors used by the antilock braking system, the electronic stability control or the automatic emergency braking, which detect that the front and rear wheels are not turning at the same speed and respond by preventing the drive wheels from turning on the dynamometer. Some vehicles detect the dynamometer conditions automatically and do not require the vehicle to be put into a "dyno" mode state.

discussed above, such claims have rarely been successfully disputed in Europe, even though these would be considered illegal defeat devices by American authorities.

Almost all manufacturers in Europe are changing calibrations outside of a relatively narrow ambient temperature window and after hot engine restarts (Bernard, 2017). For example, Figure 2 shows the results of a series of NEDC tests conducted with different engine oil temperatures at the start of the test (if the engine has been turned off for several hours, the oil and coolant temperatures at the start of the test are usually the same). Only tests conducted with engine oil temperature within the type-approval limits met the standards—all tests with engine oil temperatures both above and below the type-approval limits had elevated emissions and failed to meet the standards. Certainly, extreme low and high temperatures can affect the operation of the engine and emissions control system, but any calibration change should be based upon actual instantaneous engine temperatures, not ambient temperatures or engine temperatures at the start of a test.

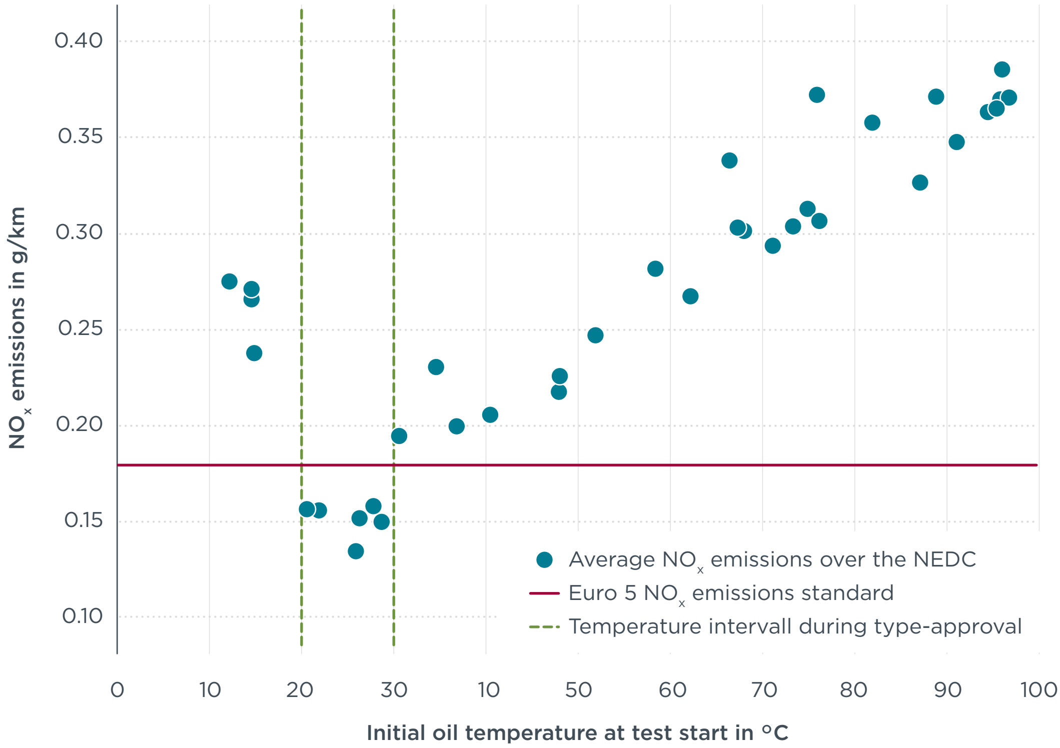


Figure 2: Average NO_x emissions of a Euro 5 diesel vehicle on an NEDC test for variable oil temperature at test start (Weiss et al., 2013).

Almost all manufacturers in Europe also change calibrations after the length of the NEDC has been exceeded, as observed for example by executing repeated runs of the NEDC, or after a restart with a hot engine. Emissions should be much lower during either a repeated driving cycle or after a hot restart, as the aftertreatment system is already up to normal operating temperature and can begin to work immediately. This is what is seen in the United States, where diesel NO_x emissions after a hot restart are only 15% of the emissions after a cold restart (see Figure 1). Yet, in Europe, the large majority of vehicles have higher emissions after a hot restart than after a cold start, which can be explained only by a defeat device (German, 2016a).

There is also evidence of the use of timers, or time-based information to signal that an official test is most likely finished. Researchers from RUB discovered evidence of this in the code of VW and Fiat's ECU (Contag et al., 2017). On the VW, the low-emissions mode was deactivated once the engine had run longer than the official test would take, based on number of engine revolutions. Another function used a configurable timer counting time elapsed after engine start or since the accelerator pedal position first exceeded a certain threshold. The Fiat 500X used total fuel burned since the start. Above 1.3 L of diesel fuel used—around twice the usual consumption during the type-approval test—the LNT was essentially deactivated. RUB also found a timer was also used in combination, which checked whether the time since start was longer than 26 minutes and 40 seconds.[7]

Opel has openly admitted to changing calibrations based on vehicle speed, engine speed and load, and barometric pressure in Europe. In fact, Opel published an eight-page justification of the need for these calibration changes (Opel, 2016). All of the calibration changes described by Opel would be considered illegal defeat devices by U.S. regulators (German, 2016b).

POSSIBLE FUTURE DEFEAT DEVICES

The defeat devices discovered so far have all been based on changing calibration outside the conditions of the official laboratory tests. To help address this, Europe has begun implementing the Real Driving Emissions (RDE) test for vehicle emissions type approval (Mock & Cuenot, 2017). RDE will help to limit the impact of defeat devices, but the new test procedure will not eliminate defeat devices that change calibration:

» Outside the RDE boundary conditions of altitude, ambient temperature, payload, positive elevation gain, and so on, because RDE boundary conditions cover only a fraction of the whole operating range of the vehicle (Ligterink, van Mensch, & Cuelenaere, 2017).

» By identifying the specific sequence of driving—RDE requires the urban portion of the test to be driven first, followed by rural and motorway—or monitoring the allowed share of each phase.

» To make deliberate use of the PEMS uncertainty margin incorporated into the RDE Not To Exceed (NTE) emissions limit to control RDE emissions below the on-road limit but above the laboratory limit.[8]

» To significantly increase emissions for the first part of the RDE on-road test of 20 minutes or 10 kilometers, and use the rest of the RDE urban, which is on average longer than 33 kilometers or 66 minutes, and total trip to balance out emissions below the NTE limit.[9]

» As a function of the time that has elapsed since the last ignition off. For a cold-start RDE test, it is required to drive the vehicle at least 30 minutes within the 56 hours preceding the test.

As RDE is implemented, there are additional ways to detect the presence of the PEMS unit or the RDE procedure. For example, calibrations could be changed based on detection of:

7 It is unclear why 26 minutes and 40 seconds was used, as the length of the NEDC test is 20 minutes.

8 Vehicle makers could tailor on-road NO_x emissions below the RDE diesel NTE of 168 mg/km for 2017 and 114 mg/km post 2020 but higher than the laboratory limit of 80 mg/km. That is possible with the use of an adaptive NO_x control that modulates emissions while driving and depending on the ongoing trip results, evaluated continuously thanks to the on-board NO_x sensor.

9 Automakers could benefit from such a strategy because most urban trips are in fact much shorter, therefore with a higher fraction of cold starts. As an example in Germany the average city trip is only 10 kilometer and 21 minutes. The ICCT showed evidence of such behavior at the European Commission Motor Vehicle Emissions Group meeting on Euro7 in March 2018 (Bernard & Dornoff, 2018)

» A connection to the OBD interface, used to obtain information such as vehicle speed during on-road testing. OBD connection is not permitted during type-approval testing.
» The installation of the PEMS unit. This could be detected in multiple ways including open rear hatch or trunk, the use of the trailer hook where the PEMS is mounted, or the change in exhaust back pressure resulting from installation of the PEMS exhaust flow meter.
» Known RDE test routes using GPS.

It is clear that the possibilities for defeat devices are endless and therefore difficult to prevent. To be effective, any testing protocol should be able to identify the presence of a defeat device, no matter how sophisticated. Realistically, this requires on-road testing, at least as an initial screening tool to find the presence of high emissions. Once a potential defeat device has been identified, the trigger for the high emissions can be found using a combination of on-road and dynamometer testing, as explained below.

DEFEAT DEVICE VERSUS OFF-CYCLE EMISSIONS

Manufacturers will always optimize for the test. Designing and calibrating powertrains and emissions control systems is expensive and difficult, especially as engineers are faced with many tradeoffs involving performance; drivability; noise, vibration, and harshness (NVH); fuel economy; durability; and emissions. Thus, engineers focus on optimizing emissions only for the conditions on the test as required by the letter of the regulations. Ideally, manufacturers would spend time to optimize emissions at all possible driving conditions, but this will occur only if required by regulation. The goal of defeat-device provisions is to make sure manufacturers don't purposely reduce effectiveness outside the conditions on the test cycle.

Where does optimization end and defeat devices begin? First, it is important to understand some basics about the emissions control system itself. For gasoline vehicles, the three-way catalyst and precise air/fuel control required to meet emissions on the test are also effective outside the test boundaries. Further, there is little tradeoff with drivability, NVH, durability, and fuel economy. Thus, except perhaps for vehicles using downsized engines where there is a tradeoff between performance and emissions, there is little incentive to install defeat devices on gasoline engines. For diesel engines, HC and CO emissions are inherently low and are rarely of concern as diesel oxidation catalysts are inexpensive and have been standard since 2000. In addition, since 2010, the Euro 5 regulation has successfully forced the use of diesel particulate filters to reduce particulate matter (PM). Thus, the primary concern with defeat devices is with respect to diesel NO_x emissions.

For diesel NO_x, control is done in two places—in the engine, mainly controlled with EGR rate and fuel injection timing and pressure, and in the exhaust aftertreatment system, either SCR or LNT.

EGR CONTROL STRATEGY

The EGR rate is controlled by the ECU and can fluctuate between 0% and 50%. The higher the EGR rate, the larger the decrease in engine-out NO_x. The EGR rate is the product of the function of several actuators, including not just the EGR valve's position but also air throttle and turbocharger position. Thus, to properly control EGR rate, the control system typically uses closed loop control, where the position of the EGR valve varies with air/fuel ratio, intake manifold pressure, intake manifold temperature, and fuel-injection quantity. In closed-loop operation, the EGR rate is typically driven by controlling the air mass flow with the EGR and air throttle actuators, while controlling the air/fuel ratio via boost pressure using the turbocharger actuator. These control points are defined using engine maps of each of the parameters and thus are highly dependent on engine speed and torque.

There is no reason why this strategy should change dramatically outside of a type-approval test. For a given engine speed, engine load, and engine coolant temperature, the fuel flow, air flow, and boost pressure should stay constant—and therefore the EGR rate should remain similar for all other normal external conditions. If the EGR rate changes in the real world for a given engine speed, load, and coolant temperature, this is a clear indication of a defeat device.

The difficulty comes at engine speed and load points that do not occur during the type-approval test, such as an engine load higher than the maximum load reached on the test. Is it OK for EGR to be shut off or reduced? As engine loads and turbocharger boost increase, the EGR valve position can be controlled to adjust the flow, but at high engine loads the EGR flow might reach its maximum, above which the ratio of

EGR flow to air flow starts to decrease. However, this reduction in EGR rate should occur only at high engine loads, and even then it should be gradual and linear. While there are a few other conditions outside the type-approval test that require EGR rate reduction, especially at cold engine temperatures, EGR should be operating normally and linearly most of the time.[10]

Unfortunately, it is much easier for calibration engineers to simply shut the EGR system off outside the test-cycle window than to optimize EGR strategy under all conditions. One of the challenges for regulators is to differentiate between conditions when EGR reduction is actually needed and when engineers are taking shortcuts. As a first general guideline, the main sensors that could trigger a legitimate reduction in EGR are engine coolant temperature, intake manifold temperature, and intake manifold pressure. Using ambient temperature, especially alone, is a red flag that the engine has been calibrated using shortcuts that unnecessarily reduce the effectiveness of the EGR system, which should also be classified as an illegal defeat device.

Another issue is that the EGR system may be sized to handle only the flow rates experienced on the type-approval test cycle. For example, the EGR system includes a cooler for EGR gases before they are reintroduced and mixed with the combustion gases. If the maximum flow rate of this cooler was designed to handle only the flow on the NEDC, the flow will be inadequate to reduce NO_x emissions at higher engine speeds and loads experienced in the real world. Is an undersized EGR cooler an illegal defeat device? In Europe, it is unlikely that this would be considered an illegal defeat device, although regulators in the United States most likely would consider it so. The EPA's guidance specifically states that calibration changes required because of the use of an inferior design are not allowed.[11]

LNT AND SCR AFTERTREATMENT STRATEGIES

The effectiveness of LNT aftertreatment systems is controlled by the frequency of NO_x purges, and the effectiveness of SCR aftertreatment systems is controlled by the amount of urea injected. The main factors that impact LNT and SCR efficiency are catalyst temperature, exhaust flow rate, and catalyst inlet NO_x concentration. The timing and frequency of LNT regeneration events or SCR urea injection should be controlled based on engine-out NO_x, catalyst temperature, and catalyst space velocity. Previous operating conditions could have a momentary impact, but the primary effect is on catalyst temperature, and other effects should be negligible, as demonstrated in Figure 3 below.

LNT and SCR catalysts typical light off around 200°C–250°C. High conversion rates after that should be expected, although very high catalyst temperatures of more than 450°C can reduce efficiency.

Aftertreatment systems are typically sized/designed for conditions of the test cycle. "Sized" typically refers to what the system can handle in terms of flow rate/capacity. Conversion efficiency over the aftertreatment catalyst declines as the exhaust flow increases, resulting from higher space velocity, or the ratio of flow rate to catalyst volume, and hence shorter residence time in the catalyst. One of the advantages of SCR over LNT is that SCR systems are capable of maintaining much higher conversion

10 A potential emissions control strategy could be to reduce EGR use after the SCR system warms up and treat the extra NO_x with urea, which lowers fuel consumption. But this is only possible after the aftertreatment warms up, so EGR rate reduction for a given speed, load, and temperature is still generally an indication of a defeat device. Measurement of tailpipe NO_x emissions can easily separate this strategy from a defeat device.

11 The EPA's guidance states: "If an AECD (auxiliary emissions control device—the EPA's term for what the EU regulation defines simply as a "defeat device" [Muncrief, German, & Schultz, 2016]) is expected to cause an excessive increase in any regulated pollutant, EPA will consider whether design alternatives are available which would make the engine/emission control system less susceptible to the need for an AECD that increases emissions to the extent of the proposed AECD" (U.S. Environmental Protection Agency, 2001).

efficiencies at higher flow rates. To maintain conversion efficiency at larger flow rates requires a larger, more expensive catalyst than is required to pass the NEDC test. As with EGR cooler size, if NO_x emissions increase at higher engine speeds and loads because the aftertreatment catalyst has been sized to the NEDC, this would most likely be considered an illegal defeat device in the United States but not in Europe.

In Europe, it was previously found that the SCR systems on Euro IV and V heavy-duty (HD) engines were not operating at low load because they were using SCR systems that did not light off below a certain temperature, around 250°C (Muncrief, 2015). These low loads and SCR temperatures occur frequently in urban conditions, resulting in high NO_x in urban conditions on Euro IV/V HD engines. To correct this, the test protocols were changed for Euro VI to require much more substantial operation at these lower loads, forcing manufacturers to install better catalysts and develop better thermal management strategies (Williams & Minjares, 2016). This illustrates the importance of properly designed emissions requirements, as high emissions due to unrepresentative test protocols do not necessarily suggest an illegal defeat device.

IMPLICATIONS FOR SEPARATING DEFEAT-DEVICE FROM OFF-CYCLE EMISSIONS IMPACTS

The issue of robust emissions control design complicates detection of defeat devices in Europe. In the United States, it is expected and required that manufacturers use emissions control systems that maintain effectiveness under all normal in-use conditions, making it easier to identify step-changes in calibration or inadequate system design. In Europe, it should not be expected that car manufacturers will make additional efforts to design their powertrain and exhaust aftertreatment systems for low emissions outside the boundaries of the regulatory test. However, it should still be expected that the system will operate the same way in the real world, barring brief exceptions to protect the engine. Thus, it is important to look for predictable and linear behavior of the emissions control system.

DEFEAT DEVICE TESTING: THEORY

Vehicles with defeat devices have low emissions when tested over the type-approval test but higher emissions in real-world operation. In general, vehicles fall into one of four categories:

1. Emissions stay low and are robust in the real world outside type-approval conditions (see Figure 3). In the best case, emissions increase slightly under higher speed and load conditions but could even be reduced when more favorable conditions are encountered. The emissions control behavior is robust and results in consistent low emissions under most real-world conditions. In this case, it is unlikely the vehicle has a defeat device.

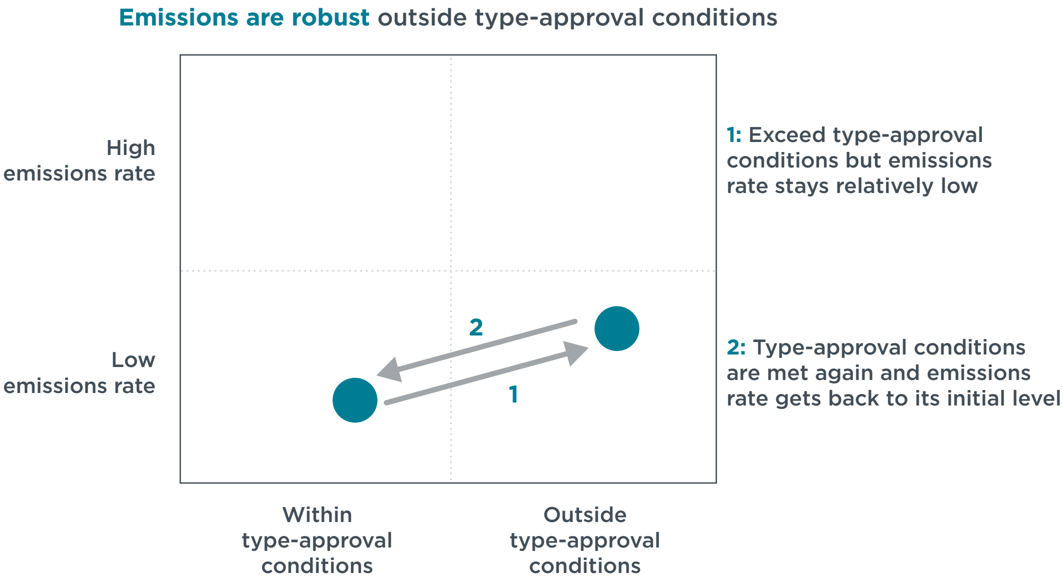


Figure 3: Emissions are low even outside the type-approval conditions. There is low suspicion of the use of a defeat device.

2. Emissions increase only when the vehicle is being tested outside type-approval conditions. Once the conditions of the test return to the type-approval range, emissions return to the low levels found on the type-approval test (see Figure 4). Such behavior alone does not necessarily indicate the presence of defeat devices, especially if the emissions increase is not too large, because it is possible that there is some logical reason for the emissions to rise. This is especially true if regulatory agencies do not consider EGR and aftertreatment systems sized to the NEDC to be defeat devices. In this case additional testing is needed to determine the presence of a defeat device.

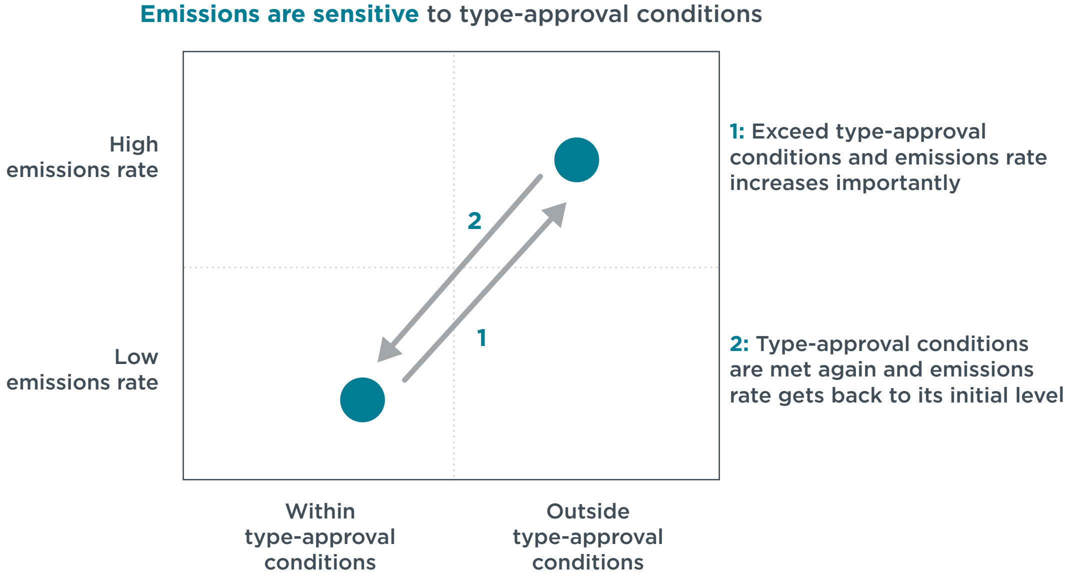


Figure 4: Emissions are high outside the type-approval conditions. There is possible use of a defeat device.

3. Emissions increase outside the type-approval conditions but then stay high independent of future conditions (see Figure 5). This is a deliberate hysteresis effect, in which emissions depend upon the driving history. Excursions outside the type-approval conditions can sometimes legitimately increase emissions, similarly to the second vehicle category, and can be justified in some cases. But emissions should return immediately to a low rate once type-approval conditions are met again. Improper hysteresis effects include programming emissions control operation to depend on the time after start, the distance traveled, an unexpected gear change, or the maximum engine speed or load reached at some point. A strategy that triggers a durable hysteresis effect on emissions rate can be considered a clear defeat device.

Emissions are sensitive to type-approval conditions and history

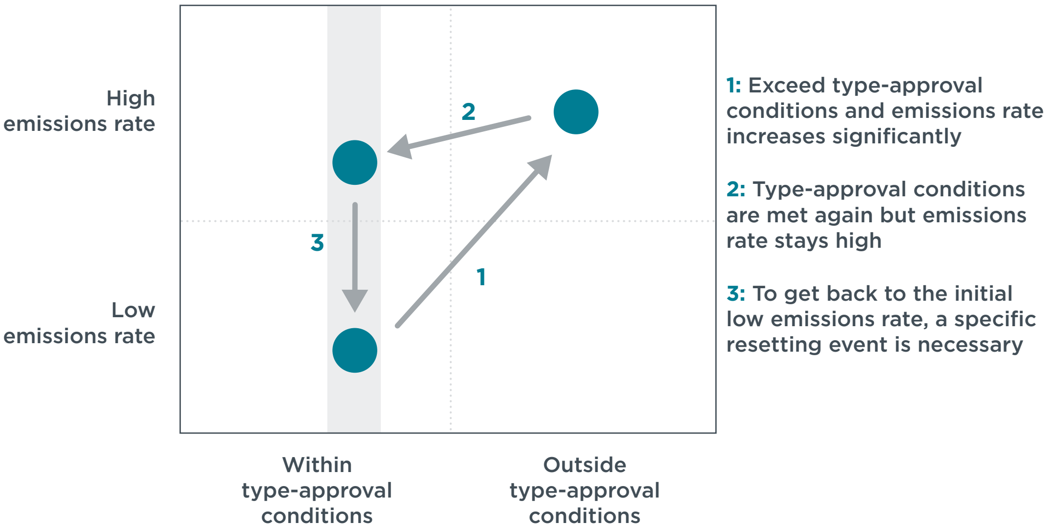


Figure 5: Emissions are high outside the type-approval conditions and stay high even when type-approval conditions are met again. There is high suspicion of the use of a defeat device.

4. Emissions increase in the real world as well as under type-approval conditions (see Figure 6). Because the vehicle exhibits high emissions within the type-approval test conditions, it is likely that the vehicle is experiencing some sort of malfunction. If this issue appears with multiple vehicles of the same model, this could also indicate a systemic conformity-of-production or durability issue that should be further investigated by compliance authorities.

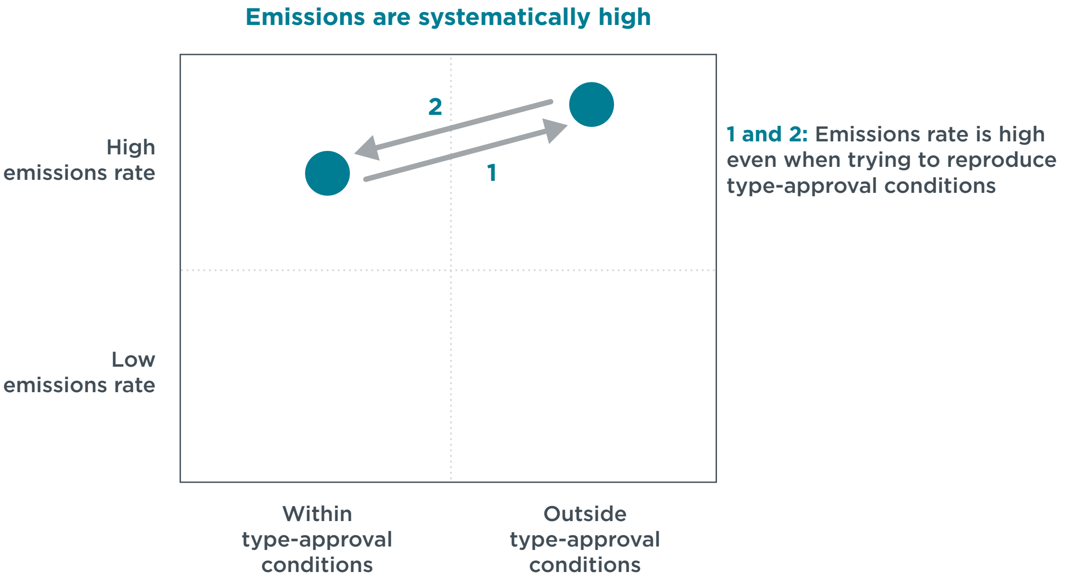


Figure 6: Emissions are high within and outside the type-approval conditions. It is likely the vehicle is malfunctioning in some way.

STEP 1: SELECT A VEHICLE FOR TESTING

Vehicle selection is important and should not be minimized. In any given model year there are more than 2,000 combinations of nameplate, Euro standard, fuel type, engine power, transmission, and driven wheels sold in the European Union. A market surveillance program would be required to test 1,500 model variants to cover 90% of 2016 EU car sales (Bernard, Tietge, German, & Muncrief, 2018). That would be a prohibitive number for annual testing.

Considerations for vehicle selection to look specifically for defeat devices include:

- **Pre-screening rather than random testing.** There are two good ways to screen vehicles: remote sensing and gathering data from government and third-party testing. In the aftermath of Dieselgate, hundreds of vehicles have been tested in the real world or using nonstandard laboratory tests. These results can be used as a guide for finding current vehicles with the highest emissions. While remote sensing has not been used extensively in Europe, it can keep track of progress in reducing emissions over time and can provide data on the entire fleet, not just the subset of vehicles that have been tested by third parties. A recent example is remote sensing conducted as part of the TRUE initiative (Bernard et al., 2018). In either case, you look for vehicle models with high emissions compared with the rest of the fleet or suspicious behavior under specific real-world conditions.
- **Grouping vehicles by attributes** most likely to affect emissions. These include manufacturer group, euro standard, fuel type, and engine displacement. Such grouping avoids testing multiple vehicles with similar characteristics, reducing the number of vehicle tests required to cover 90% of the market to around 100 in 2016 (Bernard et al., 2018). This approach is similar to the definition of PEMS test families in the Euro 6d regulation (European Commission, 2017b).
- **Selecting vehicles with lower mileage.** This will avoid confusing the effects of defeat devices with those of deterioration. Deterioration monitoring/testing is also important but is not covered in this paper.
- **Understanding impact of step-function.** Because the effect of defeat devices on emissions is generally a step-function, defeat devices used on a vehicle group with smaller sales could still have a big impact on total emissions.

These principles were not strictly applied in selecting the three vehicles for this project as we were looking for vehicles that would help develop our procedures. The three diesel Euro 6 test vehicles chosen for this project were a Volkswagen Passat (1.6L TDI) and two C-Class Mercedes (1.6L Bluetec). The Passat 1.6L TDI model was previously tested by TNO (Kadijk, van Mensch, & Spreen, 2015) and Emissions Analytics (Baldino, Tietge, Muncrief, Bernard, & Mock, 2017). It showed among the lowest on-road emissions with an average NO_x conformity factor of 1.7, ranging from less than 1 to a maximum of 3.4. The C-Class Mercedes was tested by TNO, Emissions Analytics, the German environmental group Deutsche Umwelthilfe (Baldino et al., 2017), and national authorities in Germany (Bundesministerium für Verkehr und digitale Infrastruktur, 2016). A range of values was reported over different vehicles using different engines and tests, with conformity factors of less than 1 to more than 7.5 with an average conformity factor of 2.6, suggesting these vehicles fall within the third vehicle category discussed above (see Figure 3). This disparity in the test results suggested that these C-Class vehicles would be challenging to diagnose and would help develop our procedures. Thus, we selected two C-Class Mercedes for our testing: a Mercedes C200d (100 kW, 1598 cc, SCR, model year 2015/Euro 6b) and a C180d (85 kW, 1598 cc, SCR, model year 2015/Euro 6b), both using the 1.6L engine block originally from the group Renault-Nissan. More information on vehicle specifications is in Appendix A.

STEP 2: CONFIRM TYPE-APPROVAL VERSUS REAL-WORLD EMISSIONS DISCREPANCY AND PROPER VEHICLE OPERATION

This step confirms high real-world emissions and low type-approval emissions before proceeding to the more detailed testing in Steps 3 through 5. If real-world emissions are low, the vehicle most likely does not contain a defeat device, and if type-approval emissions do not meet the standard, then there may be something wrong with the vehicle that would invalidate any attempt to identify a defeat device.

These tests—one on the dynamometer and one on the road—could be done in either order. However, it is always important to think about worst-case scenarios. It could be possible that a dynamometer test performed first could trigger a defeat device that might last throughout the course of the real-world test. Thus, we believe it is better to perform the on-road test first to obtain real-world emissions, preventing the vehicle from detecting the trial.

ON-ROAD TESTING

If possible, the initial on-road tests should be done in a non-intrusive way to ensure that the vehicle does not detect it is being tested. The NO_x sensor set-up described in Step 3 would be good for this. Real-world driving includes a wide range of speed, acceleration, altitude, elevation gain, road grade, trip length, and ambient temperature. The on-road test thus should not be confined to something like RDE — which is a relatively prescriptive way of driving that does not cover a sufficiently wide range of conditions to be considered truly "real world." To capture as many conditions as possible, try to combine short and long trips and cold, hot, and warm starts in a wide range of conditions—vary grade, speed, acceleration, etc. It is also important to conduct testing in a range of ambient conditions. If you do not gather data over a wide range of conditions, you will increase the chances of missing defeat devices based on specific triggers, such as ambient temperature. It is also beneficial to vary the location to eliminate the possibility of a GPS-based defeat device sensing that testing is being conducted in close proximity to known laboratories or test sites.

Evaluating and defining "high real-world emissions" is difficult because of the many variables that influence emissions. NO_x emissions higher than the limit of 0.080 g/km could be a normal consequence of higher engine loads or longer catalyst warmup and do not necessarily indicate a defeat device. It is not possible to give an exact emissions number that conclusively indicates the presence of a defeat device. For some background, among 67 Euro 6 vehicles tested in post-Dieselgate member-state campaigns, average NO_x emissions were 4.5 times the limit. Of these autos, 10% had a conformity factor of 1 or less, and 13% had a CF of more than 10 (Baldino et al., 2017). Assuming the member-state campaigns were performed in a manner similar to what we describe above, the only vehicles that could conclusively be excluded from further testing for defeat devices were those with a CF consistently near or lower than 1. Whether the vehicle is considered to have "high" emissions and qualify for further in-use testing will ultimately come down to the judgment of the testing organization. If time and resources allow, a good strategy is to perform this Step 2 on 5–10 vehicles and conduct follow-up testing on those that perform the worst.

If a vehicle was chosen for testing because it had high emissions based on previous third-party testing or remote sensing and the initial on-road test did not confirm the emissions, some possible reasons include:

- The previous high emissions might reflect some other reason, such as poor maintenance, tampering, or deterioration.
- The model year or ECU calibration might be different.

If resources allow, it is beneficial to confirm the initial results by testing multiple vehicles of the same model.

Figure 7 shows the emissions results of two Euro 6 vehicles on which we installed tailpipe NO_x concentration sensors. Both tests were driven on the same 25 km route within a short period of time at an ambient temperature of 2°C. Because of traffic conditions such as traffic lights, results are best compared over the distance driven instead of time.

The VW Passat (blue line) shows low NO_x tailpipe concentrations for the majority of the test. We can observe some spikes such as during acceleration to motorway speed at km 17, but the average concentration stays below 30 ppm. The Mercedes C180 shows average NO_x concentration six times higher than that of the Passat. Using the correlation work described above, we can estimate a conformity factor of about 1.7 for the VW Passat, or close to the average results measured by PEMS, and a CF of about 10 for the Mercedes C180.

Based on these results we determined that the Mercedes C-Class would be a candidate for further testing. The majority of the results were obtained with the C180 and C200 vehicle models described in Appendix A using two similar versions of the 1.6L engine equipped with SCR NO_x after-treatment. In addition, some results are shown for the VW for comparison purposes.

Figure 7: NO_x comparison between two Euro 6 diesel vehicles driven on the same route. NO_x level measured by installed sensors shows the Mercedes C180 had significantly higher NO_x emissions than the Volkswagen Passat.

For our example test vehicles, the Mercedes C180 and C200, additional on-road testing was done using the minimally invasive NO_x sensor set-up for engine-out and tailpipe emissions. Each car was tested more than three hours over one to two days, including multiple short trips and a minimum of two cold starts. The results calculated using our correlation technique are shown in Table 1 and indicate average emissions of 8.3 times the laboratory type-approval limit for the Mercedes C180 and 6.5 times for the Mercedes C200. Interestingly, the C200 had much lower engine-out NO_x than the C180, but SCR efficiency was lower.

Table 1: Results of on-road, non-RDE compliant tests on the C180 and C200. NO_x emissions were 8.3 times above the laboratory type-approval limit for the C180 and 6.5 times for the C200.

	C180		C200	
	Test 1	Test 2	Test 1	Test 2
Ambient temperature (°C)	2	7	7.4	10
Average temperature inlet SCR (°C)	219	221	221	225
Average SCR efficiency (%)	50%	56%	38%	39%
Engine-out NO_x emissions (g/km)	1.52	1.29	0.91	0.77
Tailpipe NO_x emissions (g/km)	0.76	0.57	0.56	0.47
NO_x conformity factor (ratio of on-road to type-approval limit emissions)	9.5	7.1	7.1	5.9
Average NO_x conformity factor	8.3		6.5	

LABORATORY TESTING

The next step is to perform a standard type-approval laboratory test. It is very important that any instrumentation used to measure engine and aftertreatment parameters for the preliminary on-road tests should also be installed and operating for the laboratory test, to help evaluate the causes of emissions changes during subsequent testing. The test result should be below the Euro 6 limit of 0.080 g/km of NO_x. If the vehicle fails to meet the standard, it is likely that something is wrong with the vehicle, and it will not be possible to continue with the defeat-device evaluation.[12] Figure 8 shows an example of instantaneous and total NO_x emissions during a type-approval test of the C200. Both the C180 and C200 passed the type-approval test with an average margin of 15%, at 0.068 g/km.

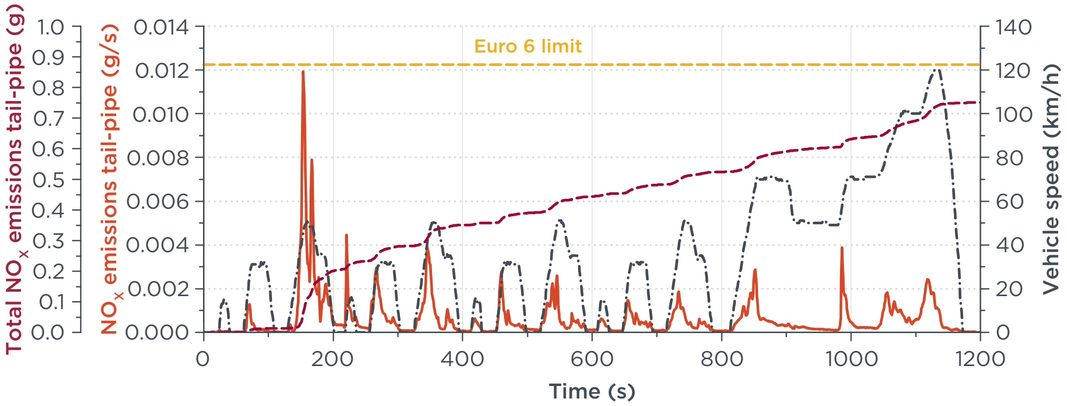


Figure 8: Instantaneous and total NO_x emissions during the NEDC type-approval test of the C200. The vehicle passed the test with a 15 % margin.

It is certainly possible to perform all the recommended on-road testing in the next section before conducting the type-approval test, but the effort could be wasted if it was later found that the vehicle was not in compliance with the type-approval test.

In the middle of testing the C200, we had to perform a type-approval test because an error code showed an abnormally high AdBlue rate on the vehicle. We took the vehicle back to the dealer, which carried out a diagnosis and made a repair. Afterward, our first step was a type-approval test to confirm that everything was functionally normally.

12 Although vehicles that fail to meet the standards are not appropriate for defeat-device evaluations, such vehicles should go through standard in-service conformity testing to investigate the causes of the noncompliance issue.

STEP 3: PREPARE THE VEHICLE FOR ROBUST EMISSIONS TESTING

A robust defeat-device evaluation program should involve laboratory chassis-dynamometer, track, and road testing. It is important to plan ahead and allow time and resources to properly incorporate all the parameters that should be measured.

Before testing, make sure the vehicle is in good working order and no engine lights are on that would indicate possible malfunctions.

Comprehensive instrumentation is a critical part of the process. Multiple parameters are needed to help identify the triggers for high emissions. It is also important to measure NO_x emissions both out of the engine and after any NO_x aftertreatment so that changes to engine-out emissions can be evaluated separately from changes in NO_x catalyst efficiency.

Thus, as many as possible of the following parameters should be measured:

» Engine-out and tailpipe emissions, assuming an aftertreatment system. It can be challenging to measure upstream of a close-coupled catalyst, but the data is valuable and is probably worth the cost of having to replace parts. Note that relatively simple NO_x concentration sensors can be used for the engine-out measurement.

» NO, NO_2, O_2, CO_2, and any other emissions of interest such as CO, HC, PM, PN. Direct measurements of emission mass flow (g/s) are best, but concentration measurements (ppm or %) can yield acceptable estimates and results, as described below.

» Ambient temperature and humidity.

» Vehicle speed.

» Elevation and grade, where grade is the change in elevation over time.

» Exhaust temperatures before and after the catalyst and exhaust flow rate.

» EGR flow rate, or at least percentage opening of the EGR valves, air throttle, and turbochargers.

» EGR-out temperature, measured after the EGR cooler and before the intake manifold.

» Intake air temperature, to help estimate the EGR rate.

» Urea solution injection rate, or at least calculate this from the NO_x reduction.[13]

» Regeneration events.

» Engine speed, air mass flow, coolant temperature, and engine relative load as a percentage of maximum load at a given engine speed.

» Intake manifold pressure and temperature.

» Fuel injection timing and pressure.

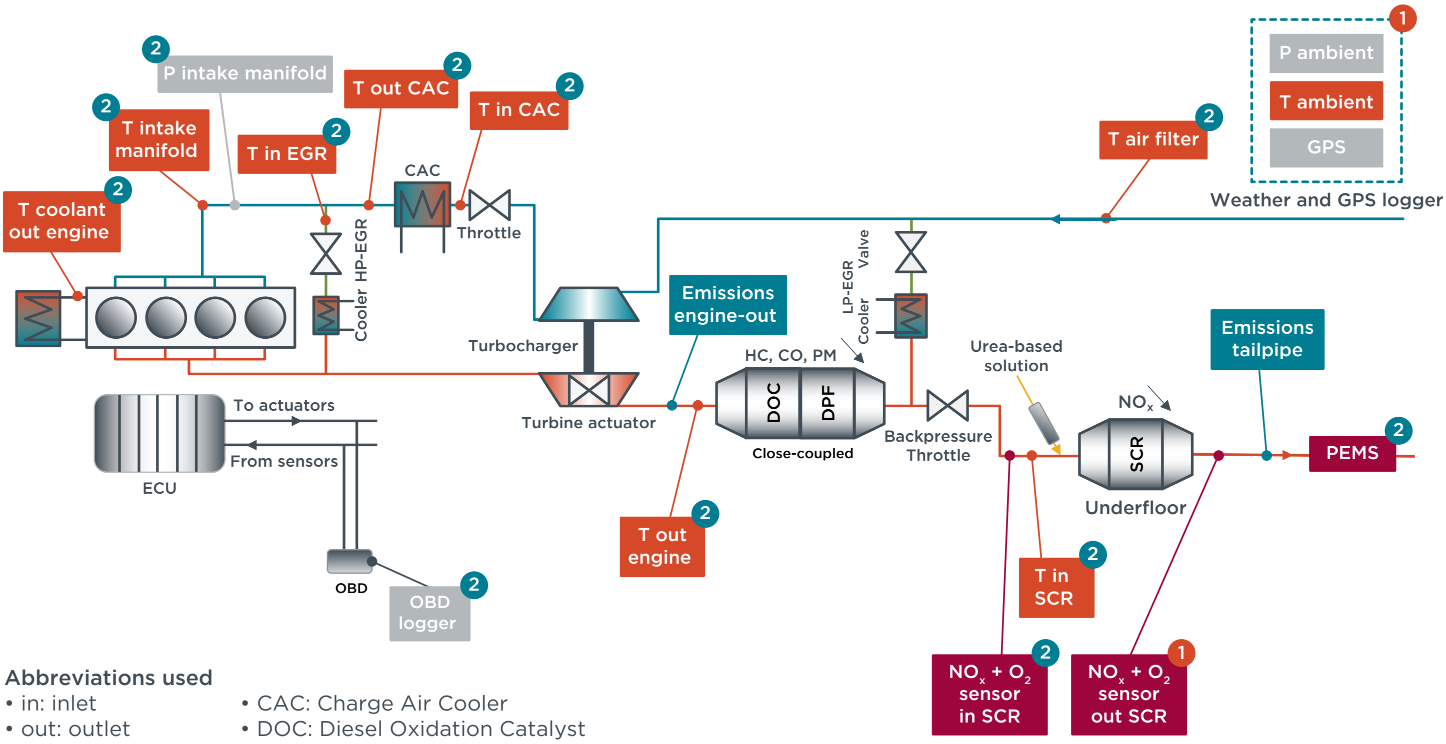
» Fuel flow rate, which is a good surrogate for load, via OBD or CO_2 if OBD is not available.

» Instantaneous fuel economy, although this can be calculated from fuel flow rate and vehicle speed.

For our testing in support of this project, we measured the parameters presented in Table 2 on the Volkswagen Passat and the Mercedes C180 and C200. The Passat and the C180 were tested first and not extensively instrumented for on-road testing. For example,

13 Urea solution consumption can be estimated by the measured amount of NO_x reduced by the SCR system (Kadijk et al., 2015). We can estimate that 1.89 ml of standard urea solution is needed to convert 1g of NO_x, assuming no ammonia overdosing.

we used a simple NO_x/O_2 sensor set-up, or level 1 presented in Figure 9. After NO_x concentration results revealed a high level of NO_x emissions for the C180, we opted to more comprehensively instrument a second vehicle, the C200, including the use of PEMS for on-road testing, or level 2 presented in Figure 9.



Abbreviations used

- in: inlet
- out: outlet
- P: Pressure
- T: Temperature
- CAC: Charge Air Cooler
- DOC: Diesel Oxidation Catalyst
- DPF: Diesel Particulate Filter
- SCR: Selective Catalyst Reduction

Figure 9: Sketch of the two levels of instrumentation. The first level (1) is not intrusive and may provide evidence of elevated emissions. The second level (2) is more intrusive and provides additional information regarding the source of emissions and the state of engine plus its aftertreatment.

These measurements are used to determine whether the engine and aftertreatment emissions strategies change inappropriately in the real world. Having these measurements allows us to evaluate whether the EGR and aftertreatment are behaving as would be expected.

Note that not all of the parameters were measured directly. Some were estimated based on other parameters. For example, it can be difficult to directly measure EGR rate. But there are other parameters that can provide an estimate of how EGR is changing. (See Appendix C.)

Table 2: Measured parameters during the laboratory and on-road testing.

	Mercedes C180 Volkswagen Passat		Mercedes C200	
Testing	**On road**	**Dyno**	**On road**	**Dyno**
Emissions measurement equipment used	NO_x/O_2 sensor	NO_x/O_2 sensor and CVS with bag sampling	NO_x/O_2 sensor and PEMS	NO_x/O_2 sensor and CVS with bag sampling
NO_x concentration (ppm)	Yes (C180 – engine out and tailpipe. Passat – tailpipe only.)	Yes (C180 – engine out and tailpipe. Passat – tailpipe only)	Yes (engine out and tailpipe)	Yes (engine out and tailpipe)
NO_x mass per distance (g/km)	Yes (Estimated from NO_x and O_2 concentration[14])	Yes	Yes	Yes
O_2 concentration (%)	Yes	Yes	Yes	Yes
CO_2 concentration (%)	Yes (Estimation from O_2 concentration[15])	Yes	Yes	Yes
CO_2 mass per distance (g/km)	Yes (Estimated from dashboard fuel economy[14])	Yes	Yes	Yes
Ambient temperature	Yes	Yes	Yes	Yes
Ambient Humidity	Yes	Yes	Yes	Yes
Vehicle speed	Yes	Yes	Yes	Yes
Road grade and elevation	Yes	NA	Yes	NA
Exhaust flow rate	No	Yes	Yes	Yes
Exhaust temperature(s)	Yes (Manifold and Inlet SCR)	Yes (Manifold and Inlet SCR)	Yes (Manifold and Inlet SCR)	Yes (Manifold)
EGR rate	No	No	Yes (Estimated from air mass flow[16])	Yes (Estimated from air mass flow[16])
EGR outlet temperature	No	No	Yes	Yes
Air mass flow	No	No	Yes	Yes
Urea injection	No	Yes (Estimated from NO_x conversion)	Yes (Estimated from NO_x conversion)	Yes (Estimated from NO_x conversion)
Regeneration events	Yes	Yes	Yes	Yes
Engine RPM	No	No	Yes	Yes
Engine load (% of full load from OBD)	No	No	Yes	Yes
Coolant temperature	No	No	Yes	Yes
Intake manifold temperature	No	No	Yes	Yes
Fuel flow rate	No	No	Estimated (Estimated from CO_2)	Estimated (Estimated from CO_2)

14 The methodology is detailed in Appendix D.
15 The methodology is detailed in Appendix B.
16 The methodology is detailed in Appendix C.

Official laboratory testing protocols can be used for general guidance in conducting testing for defeat devices. However, the standard protocol using constant volume sampling (CVS) with results based on emissions collected in the CVS is not sufficient to positively identify defeat devices. It is important to gather second-by-second emissions data and to obtain more measurements than just the basics as described above. Some chassis dynamometers are capable of gathering modal emissions data once per second in addition to bag emission concentrations.

For road or track testing, PEMS provides second-by-second emissions mass flow. Many other parameters can be obtained from the OBD system. However, just in case the ECU is looking for signs that a PEMS unit has been installed or is monitoring connection to the OBD system, a less-intrusive method is needed that cannot be sensed. Also, PEMS cannot provide engine-out emissions data. For our testing of the VW Passat, Mercedes C180 and C200 vehicles, we installed NO_x sensors that measure NO_x and O_2 concentrations. Note that this is far cheaper than PEMS testing and still yields reasonably reliable results. The ICCT has developed a method to estimate NO_x g/km using average NO_x concentration from sensors plus an estimate of the CO_2 concentration and total trip fuel consumption. See Appendix D for a detailed description of the methodology and correlation analysis. This is essentially nonintrusive because the sensor has its own controller and does not require communication with the vehicle's ECU/OBD.

The developed correlation was verified on additional trips with the C200 where both NO_x sensor and PEMS were used without information collected from the OBD. Figure 10 confirms that NO_x mass emissions can be predicted reasonably accurately with this method. The NO_x sensor set-up can be even more accurate once we connect the OBD, as the air mass flow information can be used to calculate second-by-second mass emissions of NO_x. The Smart Emissions Measurement System was a similar solution used by the Netherlands Vehicle Authority in the investigation following Dieselgate (RDW, 2016).

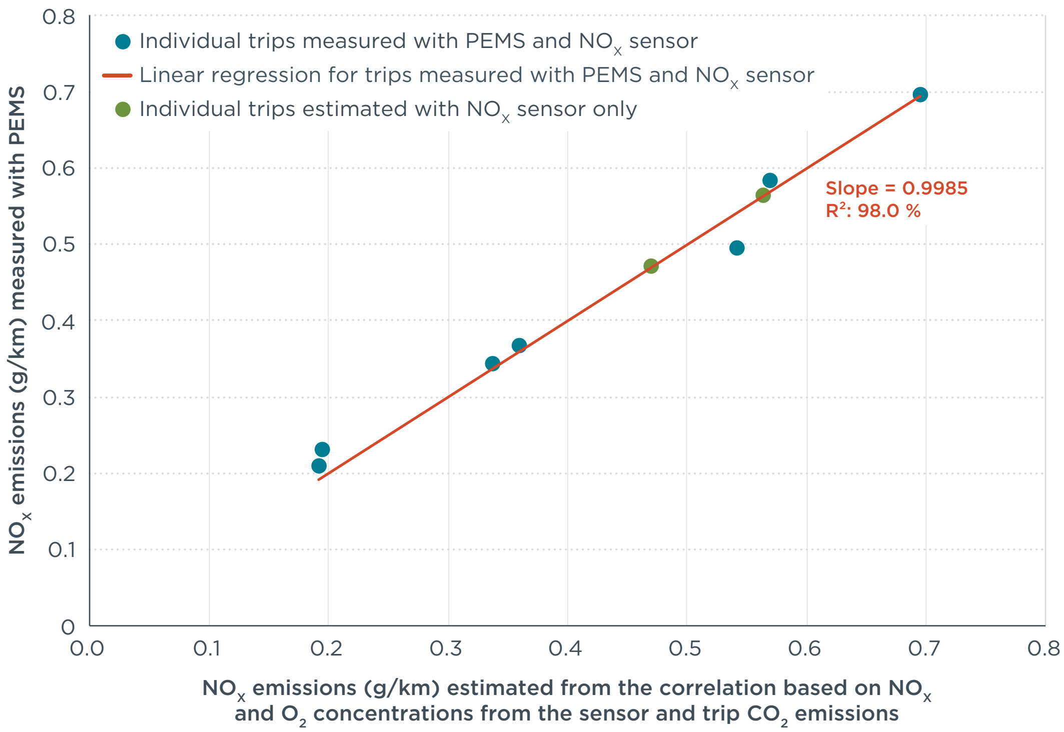


Figure 10: Verification of the developed correlation based on trips using NO_x sensor and PEMS.

Regeneration of the diesel particulate filter (DPF) is a complication for testing diesel vehicles, as both particulate and NO_x emissions may increase dramatically during regeneration. While we measured DPF regeneration during our testing, for the purpose of this exercise we did not consider tests where DPF regeneration occurred or those tests right after it occurred when the system was recovering. Note that if defeat devices that reduce EGR are in use, it is likely that DPF regeneration is happening much less frequently, as high engine-out NO_x reduces PM emissions. So, it is good to track the frequency of DPF regeneration during vehicle testing. On average, active DPF regeneration occurs once every 400–800 km for most diesel cars.

STEP 4: IN-DEPTH ROAD TESTING

Assuming that Step 2 confirms high real-world emissions and low type-approval emissions, the next question is what is causing the change? We identify this by (a) mimicking the laboratory conditions step-by-step on the road and (b) mimicking the road conditions in the lab. Changing a small number of variables or ideally just one at a time is the best way to narrow the cause and find the trigger for a defeat device, keeping in mind that one vehicle could have multiple defeat devices and multiple triggers. Repeat testing is also important for data integrity. If tests are not giving repeatable results, it could be a sign of a defeat device trigger. It is also beneficial to keep the test protocol flexible. If you see something strange, add tests and investigate.

Step 4 addresses the road testing component of this strategy. The idea is to start from the real world and step-by-step get closer to the laboratory, as depicted in the road testing flow chart (see Figure 11). Step 4 starts from the second orange rectangle of the flow chart, On-road test, RDE compliant. This section is organized into separate discussions of RDE and on-track testing, with each discussion followed by examples from our testing of the Mercedes C180 and C200 vehicles.

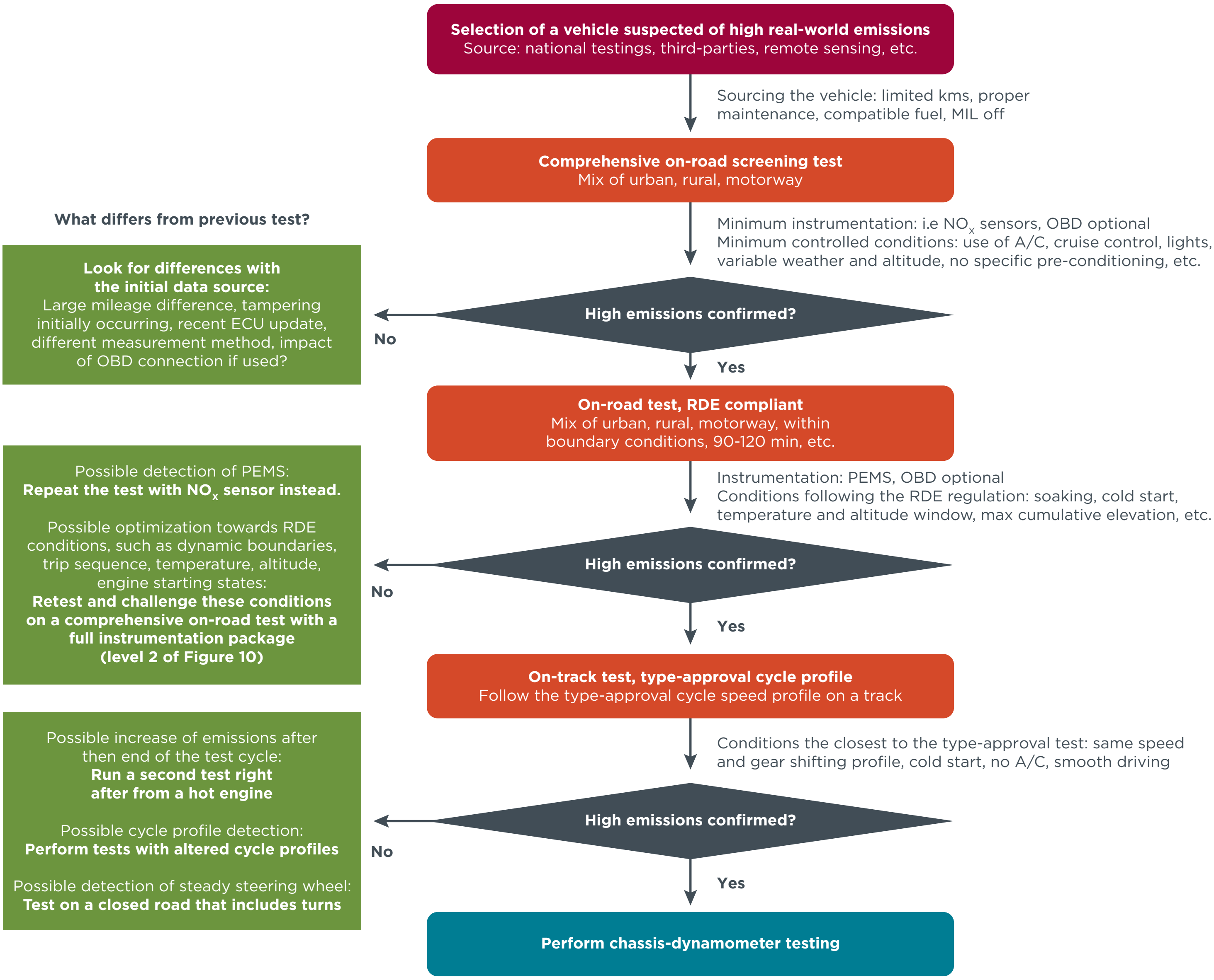


Figure 11: On-road step-by-step approach for defeat-device testing.

RDE TESTING

The testing in Step 2 generated data over a wide spectrum of on-road driving conditions. The next step in moving toward the laboratory test is to perform a regulatory RDE test. It is likely that future defeat devices will be focused on identifying that an RDE test is being performed, so comparison of RDE tests with the more comprehensive data gathered in Step 2 will become even more important as RDE-compliant vehicles are introduced in the market.

The test procedure for RDE is well documented and will not be repeated here. Keep in mind that RDE testing requires a specific mix of urban, rural, and motorway driving in a certain order, ambient temperature and altitude in an "admissible range," limits on cumulative elevation gain, limits on speed, limits on speed times acceleration, which is similar to power demand, and the use of PEMS. Both the urban driving part of the RDE and the urban part of the laboratory type-approval test start with a cold engine and with comparable driving styles. A key difference is that the urban part of the RDE is typically around five times longer in distance than the urban portion of the NEDC and also much longer than the urban part of the WLTC. This is because the RDE regulation sets minimal criteria on the 90-minute duration of the test and 16 km share of urban driving (European Commission, 2017a). Therefore, the cold-start portion of the RDE test is weighted much less than the cold-start portion of the type-approval test. As the emissions control system is warmed up for a larger fraction of time, it would be reasonable to expect average emissions on the urban phase of the RDE to be lower than average emissions over the urban portion of the type-approval test.

As a specific example of how this might work, we conducted RDE testing on the Mercedes C200. This testing was run on a regular road with the influence of traffic, so the tests could not exactly be duplicated. The RDE test was conducted four times using PEMS and a connection to the OBD to calculate second-by-second NO_x emission rate from the NO_x concentration sensors. Figure 12 shows that the vehicle's speed was similar during the four RDE tests. All of the tests were started with a cold engine. The vehicle was either soaked overnight in the laboratory workshop when performing a test in the morning, or force-cooled with a fan for tests during the same day in the afternoon. All trips were valid according to RDE trip characteristics and normality.

Figure 12: Vehicle speed over the distance driven. The same RDE-compliant test is repeated four times.

Results from the RDE testing of the C200 are summarized in Table 3, with separate columns for the urban, rural, and motorway portions of each of the four RDE tests. Full results are shown in Table 18 in Appendix E. The average NO_x emissions over the four tests were not repeatable and CFs ranged from 2.6 to 7.3. Figure 13 compares cumulative NO_x emissions for the four runs over the distance driven with the Euro 6 type-approval laboratory and on-road Euro 6d-TEMP limits shown for comparison. Runs 1 and 4 had cumulative NO_x emissions more than double those of Runs 2 and 3. This is unusual behavior, exhibiting a significant emissions variation for very little change in test conditions. Note the inconsistencies in engine-out NO_x and SCR conversion efficiency. Engine-out NO_x was reasonably consistent from runs 1 through 3, but run 4 was more than 50% higher, perhaps because of an EGR calibration trigger around 10°C. SCR conversion efficiency on Run 1 was just a third that of runs 2 and 3, even though ambient temperatures were similar on runs 1 and 3. Run 1 SCR conversion was also half that of Run 4, even though ambient temperature was higher on Run 1. The very low SCR conversion on the rural and motorway portions of Run 1 is especially difficult to explain.

Table 3: Results of RDE-compliant test repeated four times on the same route. More detailed results can be found in Appendix E.

	Run 1				Run 2				Run 3				Run 4			
	Total	urban	rural	motorway	Total	urban	rural	motorway	Total	urban	rural	motorway	Total	urban	rural	motorway
Engine-out NO_x (mg/km) from sensor	813	605	1,301	431	690	533	1044	406	857	557	1290	471	1200	1,314	1511	832
Tailpipe NO_x (mg/km) from sensor	608	435	1,047	260	196	486	195	73	201	146	294	110	553	1,257	593	146
Tailpipe CO_2 (g/km) from sensor	127	155	126	113	129	148	135	114	134	172	136	110	137	165	139	120
Average SCR NO_x conversion (%)	25	28	20	40	72	9	81	82	77	74	77	77	54	4	61	82
Average SCR inlet temp (°C)	222	185	245	266	218	170	258	266	231	192	264	267	247	212	263	292
Estimated average EGR rate (%)	14	21	2	20	17	23	9	18	13	22	5	11	5	6	4	1
Ratio to Euro 6 limit (NO_x conformity factor)	7.28	5.27	12.56	3.31	2.87	5.82	2.81	1.09	2.62	2.28	3.66	1.49	6.19	12.94	7.38	0.82
Average ambient temp (°C)	12	11.3	12.3	13.3	14.6	14.5	14.14	15.39	12.7	12.6	12.6	13.3	9.4	8.5	9.6	10.8

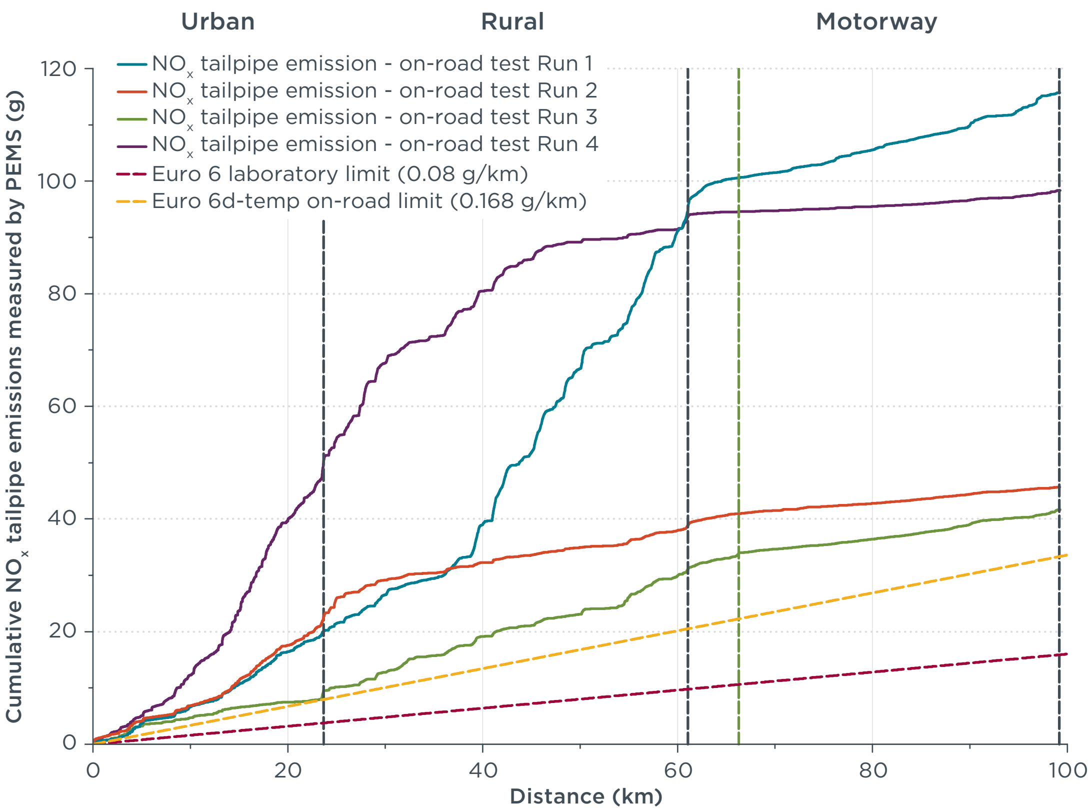


Figure 13: Cumulative NO_x emissions over the distance driven. The same repeated route leads to variable NO_x emissions from 2.6 to 7.3 times above the laboratory type-approval limit.

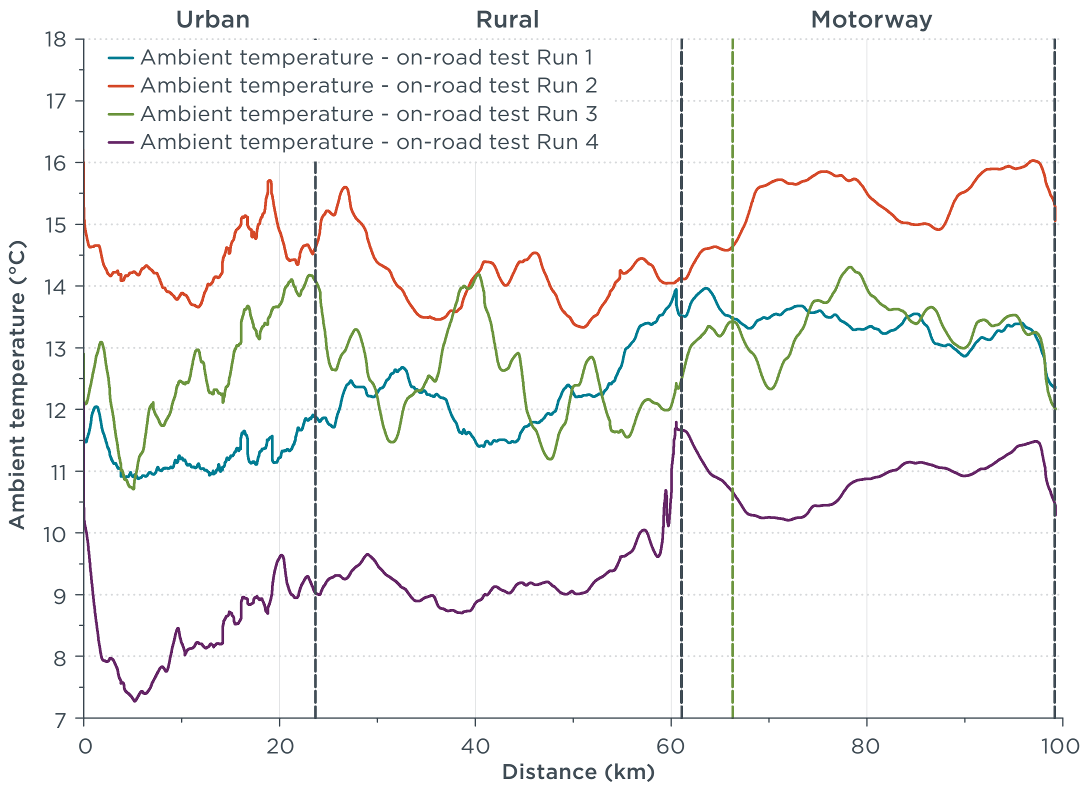


Figure 14: Ambient temperature over driven distance comparison for the repeated RDE-compliant runs.

Run 4 had the overall lowest ambient temperature. Second-by-second ambient temperature for the four runs are shown in Figure 14. Run 2 had the highest ambient temperature, and Runs 1 and 3 were in the middle. NO_x levels of Runs 1 and 4 were similar to those in the tests performed during Step 2 at ambient temperatures between 2°C and 7°C.

These results point to some initial findings, although they also indicate that further testing is needed to identify triggers for high emissions:

» Ambient temperature. The results indicate that ambient temperature may be a defeat-device trigger, reflecting small changes in ambient temperature leading to relatively large changes in emissions. This is especially evident for engine-out NO_x.

» OBD connection. These results show that the OBD connection used in the RDE runs is not a defeat device trigger, since emissions levels were similar for tests performed with and without the OBD interface.

» There may be two strategies for EGR. As shown in Figure 15, created using data presented in Table 3, average EGR rate is mostly clustered in either the 20% or the 5% range, suggesting two EGR strategies—a high EGR strategy and low EGR strategy. Tests with higher EGR rates tended to have higher average ambient temperatures than the tests with lower EGR rates. This was especially true for the urban and motorway portions of the RDE test, again indicating the possibility of an ambient temperature trigger. In addition, on the rural portion of the test, EGR rate was less than 10% at all ambient temperatures and less than 5% on Runs 1, 3, and 4. We are not aware of any technical reason why EGR rate should be so low on the rural segment.

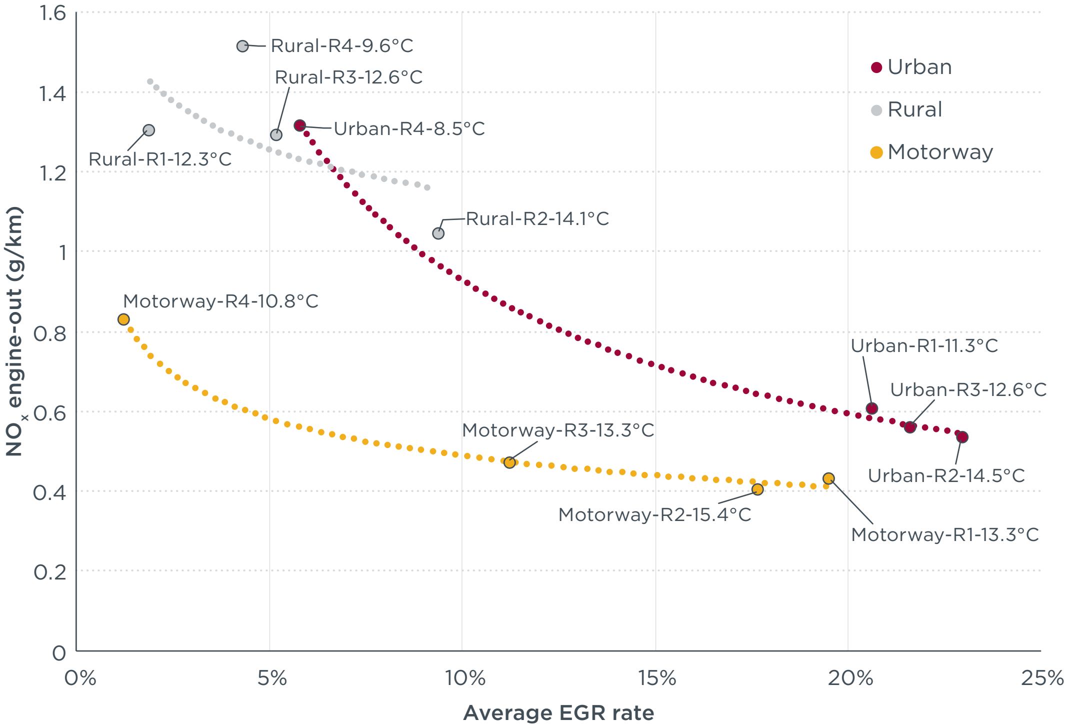


Figure 15: Average NO_x engine-out emissions and average EGR rate for the repeated RDE-compliant tests and link to ambient temperature.

» There may be multiple strategies for SCR urea injection. As shown in Figure 16, Run 2 had an average SCR NO_x conversion efficiency of 72%, and Run 3, 77%. Run 1 had only 25%, and Run 4, 54%. SCR conversion efficiency can be limited by catalyst temperature. However, the results do not show a dependence on SCR catalyst temperature. Instead, the SCR conversion efficiency had seemingly random changes. For example, in Run 1 efficiency seemed to change after 38 km, with emissions suddenly increasing, indicating some sort of trigger. It is possible that the trigger is related to ambient temperature—as can be seen in Figure 14, ambient temperature dipped to about 11.5°C right around the time that emissions increased during Run 1.[17] On the other hand, during Run 4 the ambient temperature was at least 2°C colder at less than 9.5°C. The average SCR NO_x conversion during the rural portion of Run 4 was 60%, three times higher than the 20% NO_x conversion measured during the rural portion of Run 1. This suggests the trigger may be more complicated than ambient temperature alone.

17 Note that the ambient temperature for our test was measured separately from the vehicle's temperature sensor.

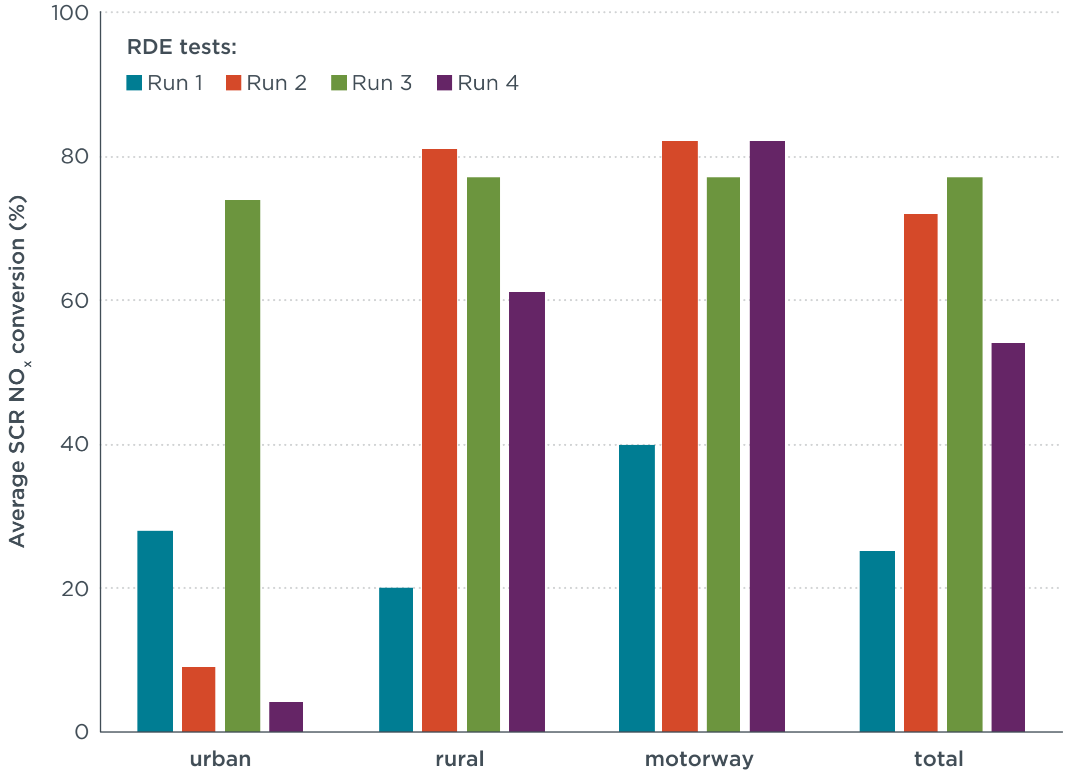


Figure 16: Average SCR NO_x conversion during the different portions of the repeated RDE-compliant runs.

MIMIC THE TYPE-APPROVAL TEST ON A TRACK

After conducting RDE tests, the next step toward the laboratory test is to mimic the type-approval test on the track (see Figure 11). It can be difficult to precisely mimic the NEDC on a track, as you need a flat track, a visual aid for the driver to follow the NEDC speed trace during the test, ambient temperature between 20°C and 30°C, and to follow the prescriptive preconditioning and cold-start requirements of the type-approval test.

As a specific example of how this might work, we mimicked the type-approval test using the Mercedes C200. While we aimed to follow as closely as possible the NEDC test on the track, key differences are acknowledged in Table 4.

Table 4: NEDC tested on-track compared with laboratory type-approval.

Test element	NEDC on track	Type approval test
Test details	PEMS	CVS
	On a closed track	2WD chassis dynamometer
Preconditioning cycle (3x EUDC)	No	Yes
Cold start	No	Yes
Grade	None	None
Speed profile	NEDC	NEDC
Ambient temperature (°C)	16	23

The Mercedes C200 was driven following the NEDC speed profile free from traffic conditions on a closed, high-speed track. The test was repeated twice during the same afternoon. It was not possible to perform the test from a cold start, so these were hot-start tests. Ambient temperature was between 15°C and 16°C, below the type-approval range, and there was no specific vehicle preconditioning.

A summary of results for the two on-track NEDC tests is shown in Table 5, with full results shown in Table 19 in Appendix E. The emissions results were consistent for the two tests, including engine-out emissions and SCR efficiency. The results are also similar to those from RDE Run 2 and Run 3 in Step 4. Average CO_2 emissions during the on-track tests were about 10% higher than in the laboratory type-approval cold-start test, and tailpipe NO_x was approximately three times higher than the type-approval limit. This is significant considering that the tests follow the same driving profile and a hot-start test with a warmed-up engine should yield lower, not higher, emissions as the catalyst is already up to operating temperature. Figure 17 compares the engine-out and tailpipe emissions for the average of the two on-track NEDC tests with those of the official NEDC test conducted on the chassis dynamometer in Step 2. It can be seen that the engine-out NO_x is almost five times higher for the on-track tests, whereas the average SCR conversion is significant and similar for both tests—58% for the dyno tests and 66%–67% for the on-track tests. This indicates that the higher emissions for the on-track test were most likely driven by a change in EGR control strategy. There are only a few reasons why this could happen, all of which suggest the presence of a defeat device:

- An EGR strategy that is less effective when the engine is started warm than after a cold start. This was one of the main differences between the type-approval and on-track testing as shown in Table 4.
- A trigger for ambient temperature, as these tests were done at 15°C. This was slightly higher than the possible trigger found during RDE testing of 10°C–12°C, but there may be a strategy that ramps down EGR outside the type-approval window.
- There might be a trigger related to the lack of prescribed preconditioning.
- It could also be possible that there is a defeat device sensing that the vehicle is being driven on a track instead of on a dynamometer. However, this is not likely in this case, as emissions for RDE Runs 2 and 3 were relatively low and SCR activity was still significant during the on-track NEDC test.

Table 5: Summary of key results from the Mercedes C200 NEDC on-track test.

	On-track NEDC 1	On-track NEDC 2
Engine-out NO_x (mg/km), from sensor	798	781
Tailpipe NO_x (mg/km), from sensor	274	257
Tailpipe CO_2 (g/km), from sensor	157	151
Average SCR NO_x conversion (%)	66	67
Average SCR inlet temp (°C)	213	214
Average estimated EGR rate (%)	21	19
Ratio to Euro 6 limit (NO_x conformity factor)	3.43	3.21
Average ambient temp (°C)	15.6	15.6

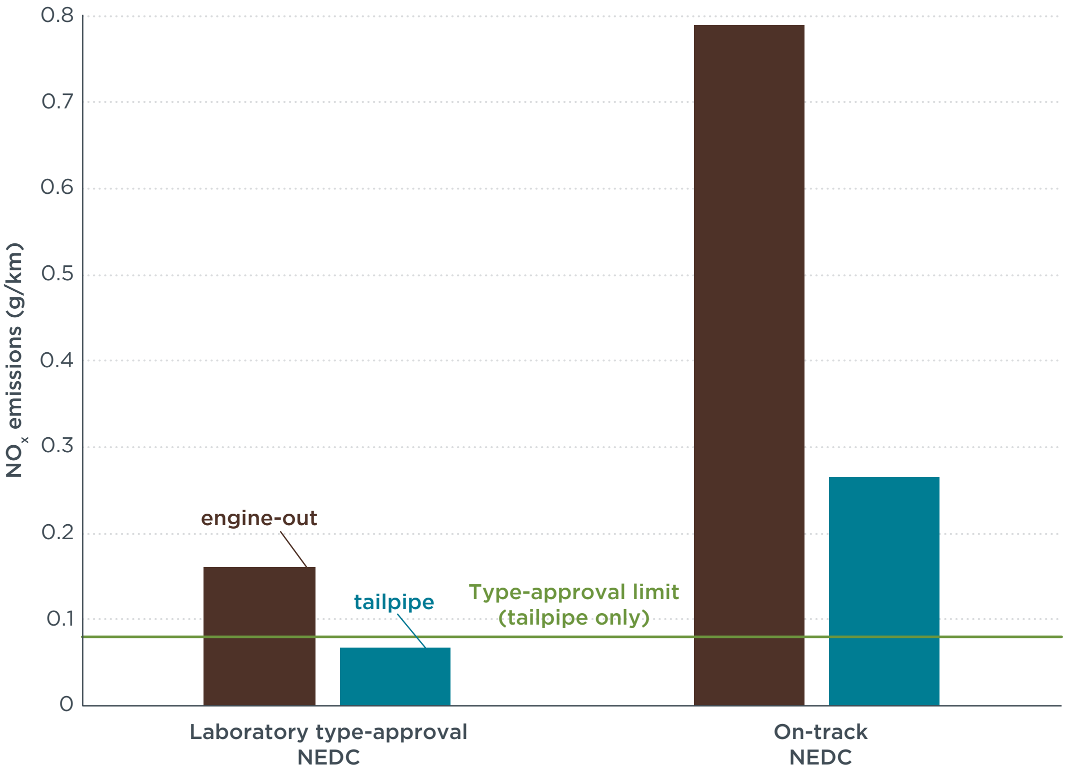


Figure 17. Engine-out and tailpipe NO_x emissions for the official NEDC type-approval test conducted on the chassis dynamometer compared with the NEDC driven on a track (average of two tests).

ADDITIONAL ON-ROAD TESTING

The flow chart for on-road testing suggests conducting additional testing when the results are contradictory or confusing. We have a specific example of that here, as we were confused about the unrepeatability of the road-based RDE tests on the C200. To address the inconsistency, we conducted additional testing based on the urban portion of the RDE test. To enhance repeatability of the measurements, the testing was conducted on the track described earlier, with the driver guided through a series of signs indicating speed, distance to accelerate/decelerate, and duration of the stop. This lap around the track was repeated 14 times to match the RDE urban requirements, including test length (see Figure 18). The purpose was to study how emissions change lap after lap.

The urban speed profile was very repeatable for this test, as the test was done on the track. The average ambient temperature throughout the test was 13.1°C; the minimum and maximum ambient temperatures were 12.7°C and 13.4°C. There was no particular preconditioning of the vehicle. The test was carried out starting with a cold engine, although there was a short drive from the laboratory to the track at speeds below 45 km per hour before the start of the urban laps.

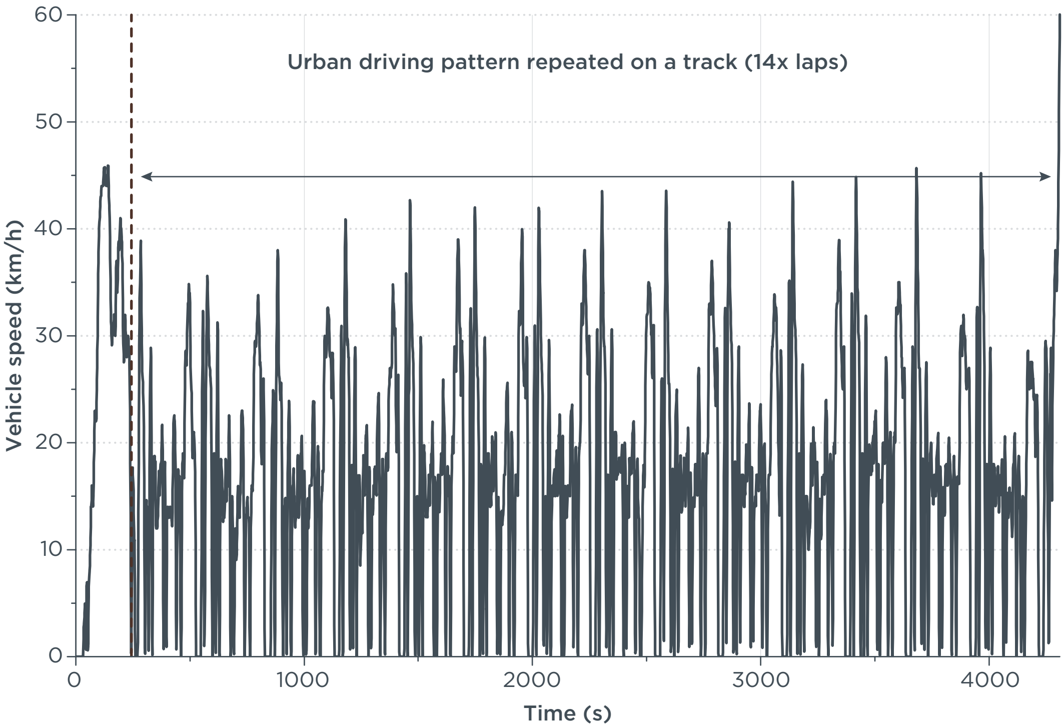


Figure 18: Vehicle speed during an RDE test performed on a track. The urban section consists of driving the car 14 times around the same lap.

Tailpipe emissions are shown in Figure 19 and Figure 20, and key test results are summarized in Table 6. Full test results can be found in Table 20 in Appendix E.[18] Tailpipe emissions were initially high on lap 1, immediately following the cold start.[19] Tailpipe emissions then decrease from lap 1 to lap 3 to a level close to the type-approval limit, or 11% above the limit as measured with a NO_x sensor. After the third lap, which was in line with the duration of the NEDC test, tailpipe NO_x emissions increased rapidly for laps 4 and 5, then stabilized through lap 9 before rapidly increasing again for laps 10 through 12. Emissions during laps 12 through 14 were more than eight times the type-approval limit.

Average engine coolant temperature increased from 63°C to 87°C over the first three laps and then stabilized.[20] Similarly, average exhaust temperature measured at the inlet of the SCR catalyst increased from 150°C to 212°C and stabilized after lap 3. Thus, engine and SCR operating conditions did not contribute to the emission changes after lap 3.

Engine-out NO_x emissions more than tripled from lap 3 to lap 5, then remained relatively constant through lap 14. SCR NO_x conversion behavior was quite different, as it was highest from laps 3–9 at more than 75% and then declined to 54% from laps 9–12. Figure

18 The emissions results were not affected by DPF regeneration, as no regeneration events occurred during this test.

19 The NO_x sensors used for our measurements were not active during the first minutes of the test to protect them against water condensation. During that time, we relied only on the measurement from PEMS tailpipe, and we cannot calculate a NO_x conversion efficiency.

20 The engine warming up explains the significant reduction of CO_2 emissions from lap 1 to 3.

21 through Figure 23 and their related discussion investigate the potential causes of these changes.

Table 6: Results of the urban part of the RDE test performed on a track, with the same lap repeated 14 times. Cells left blank represent data when the NO_x sensors were not yet active.

LAP	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Engine-out NO_x (mg/km) from sensor	-	378	401	710	1,324	1,301	1,173	1,233	1,156	1,314	1,349	1,403	1,333	1,529
Tailpipe NO_x (mg/km) from sensor	-	115	89	145	267	250	267	284	289	417	501	641	613	649
Tailpipe NO_x (mg/km) from PEMS	314	115	113	194	340	322	334	415[21]	346	448	536	661	656	683
Tailpipe CO_2 (g/km) from PEMS	324	267	234	235	226	223	217	260[21]	220	223	222	221	209	208
Average SCR NO_x conversion (%)	-	70	78	80	80	81	77	77	75	68	63	54	54	58
Average SCR inlet temp (°C)	151	202	205	212	212	210	209	212	210	209	212	212	211	210
Average estimated EGR rate (%)	3	36	37	30	19	21	19	20	19	19	18	17	19	16
Average coolant temp (°C)	63.1	78.4	86.9	89.0	89.9	90.0	90.1	90.4	90.1	89.8	89.6	89.6	89.9	90.1
Ratio to Euro 6 limit (NO_x conformity factor)	3.92	1.43	1.42	2.42	4.26	4.03	4.18	5.19	4.33	5.60	6.70	8.26	8.20	8.54
Average ambient temp (°C)	13.7	13.5	13.3	13.3	13.2	13.1	13.1	13.1	13.1	13.1	13.1	13.0	13.0	12.8

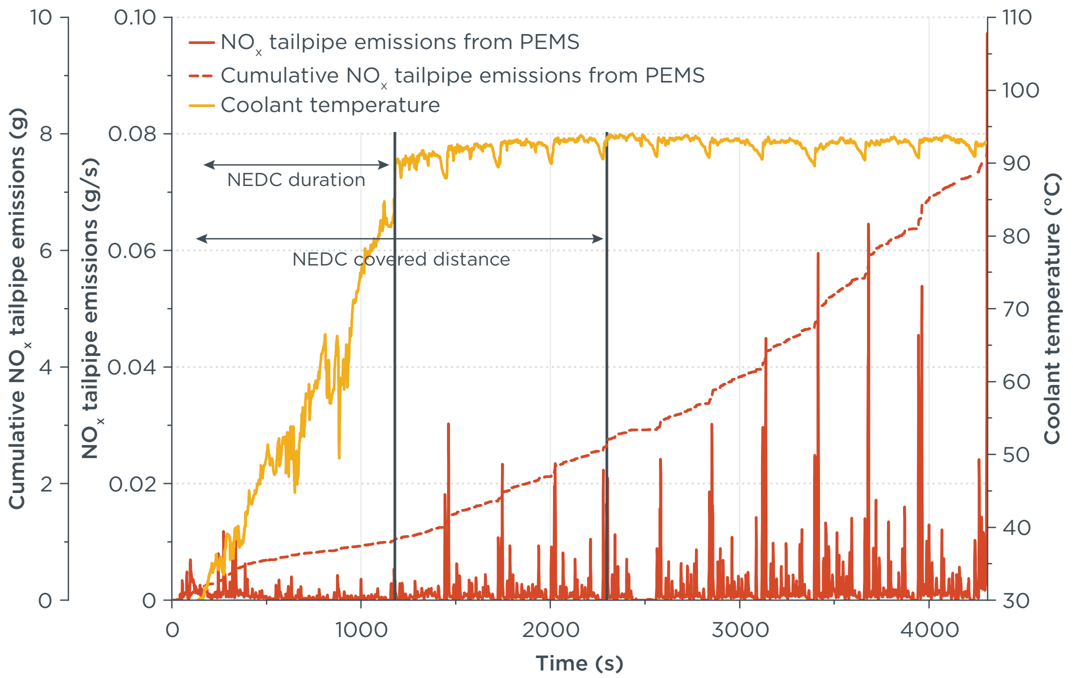


Figure 19: Instantaneous and cumulative tailpipe NO_x emissions. Emissions rate increases once the engine coolant reaches warm-up level and over time.

21 The signal from the PEMS equipment was lost for a distance of 400 m during lap 8. We excluded that portion of the lap when we recalculated distance-specific emissions from PEMS, but lap 8 cannot be directly compared with other laps. However, emissions measurement with NO_x sensors was not impacted during that lap.

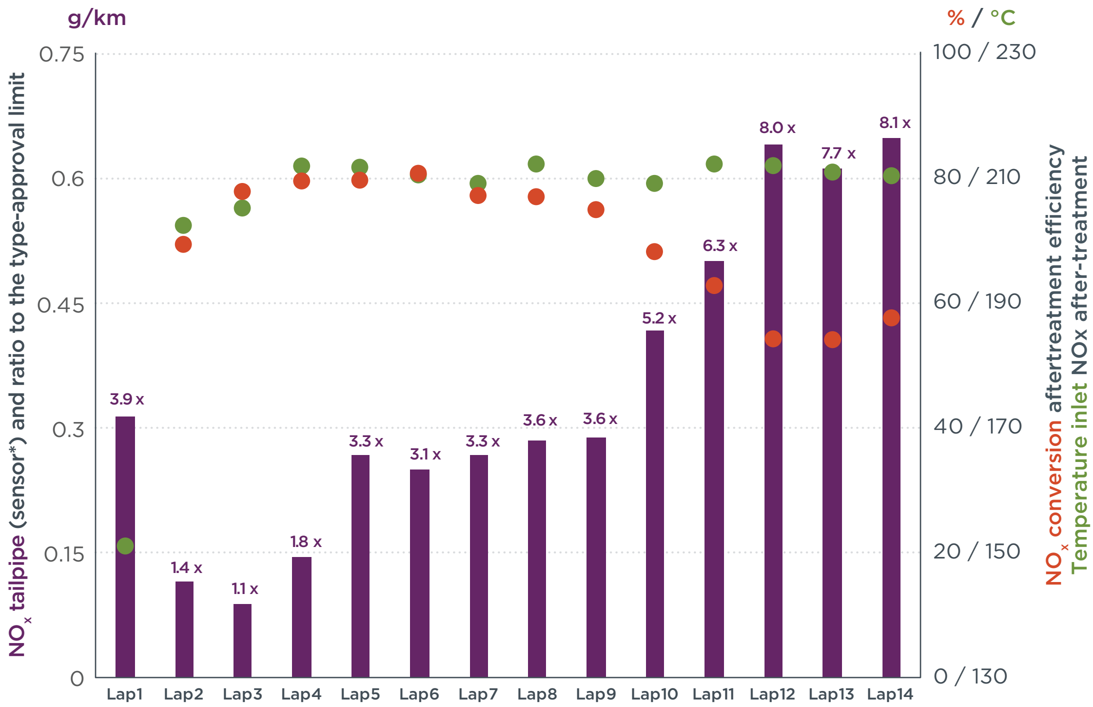


Figure 20: NO_x tailpipe emissions per kilometer, engine coolant temperature, and SCR conversion efficiency for each of the 14 laps of the urban part of the test. (*) NOx emissions for the first lap are reported from PEMS.

Engine-out emissions results are shown in Figure 21 and Figure 22. Measured engine-out NO_x emissions were the lowest for laps 2 and 3 and then more than tripled between laps 3 and 5 in parallel with a reduction in estimated EGR rate from more than 35% to less than 20% (see Figure 22). It is clear that this reduction in the EGR rate was primarily responsible for the engine-out emissions increases.

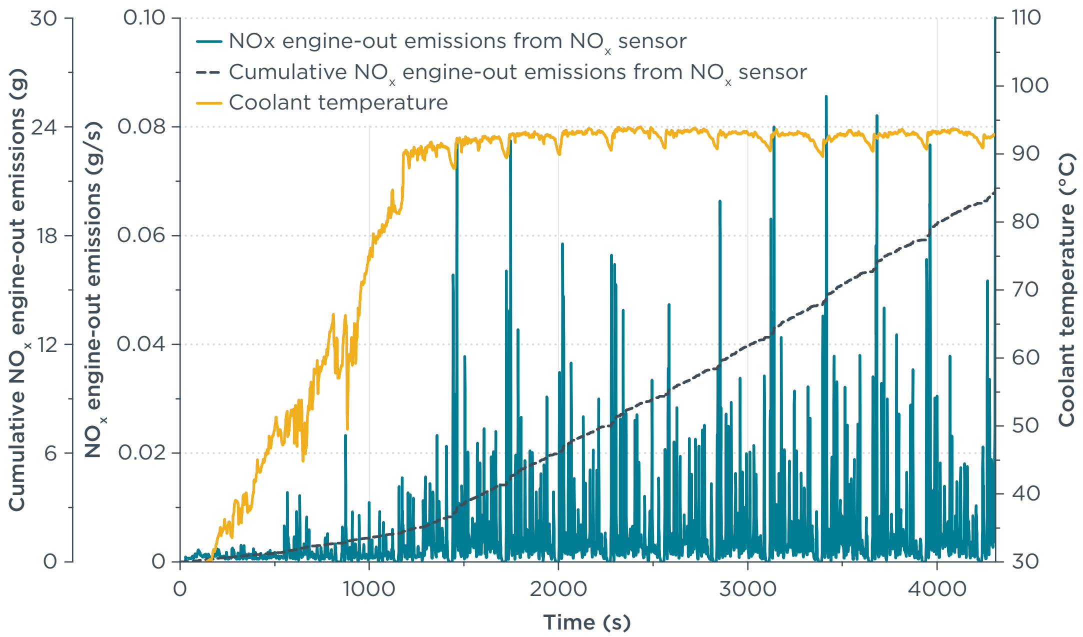


Figure 21: Instantaneous and cumulative NO_x engine-out emissions. Emissions rate increases once the engine coolant reaches warm-up level.

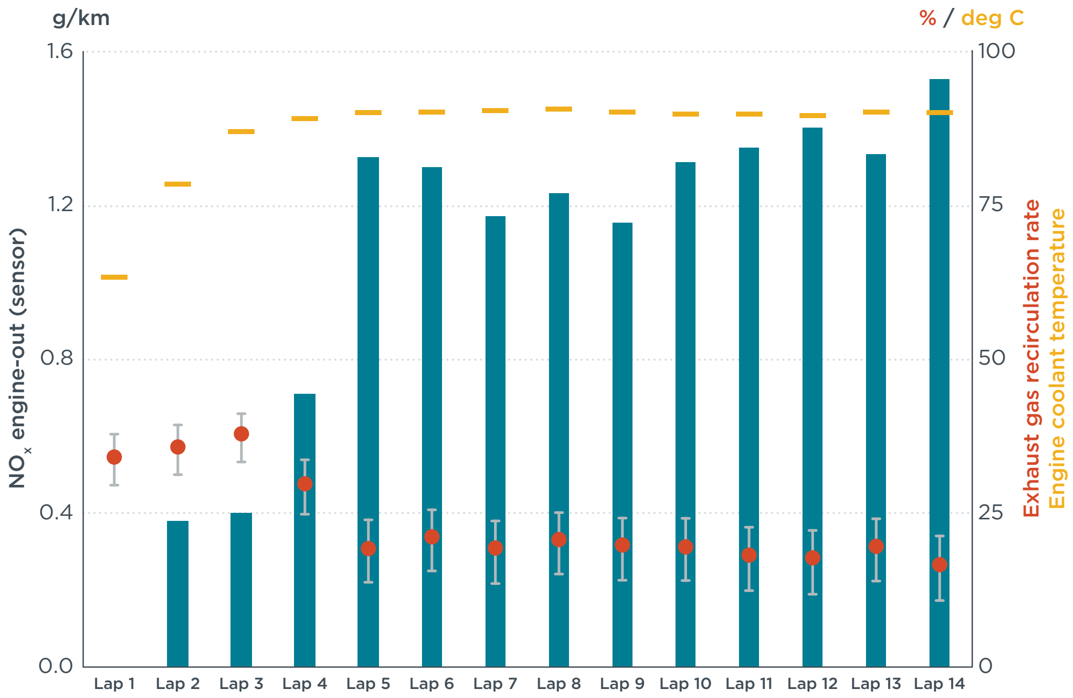


Figure 22: NO_x engine-out emissions per kilometer, engine coolant temperature and estimated EGR rate for each of the 14 laps of the urban part of the test. The error bars represent +/- 5 % around the hypothesis of a volumetric efficiency of 80%.

Figure 23 shows the urea consumption per 1,000 km for each individual lap during the test—the blue points connected by dotted lines. It also shows the average cumulative urea consumption for the entire test—the blue solid line. Actual urea consumption is compared with the consumption that would have been required to reduce NO_x emissions to the type-approval limit—the green lines—based on the actual engine-out NO_x emissions for that lap.[22] The required and actual urea consumption per lap started to diverge after lap 4 and rapidly accelerated after lap 9.

It can also be seen that total average urea consumption appears to begin to level off to a rate of around 1.3 L/1,000 km. According to Mercedes, a full urea tank should last for the entire maintenance interval.[23] In the case of the C200 we tested, the 24–25 liters in the urea tank should cover about 19,300 km, meaning a maximum average urea consumption rate of 1.27 L/1,000 km. It is possible that the reduction in SCR efficiency after lap 9 is triggered by the desire to reduce the urea consumption rate.

22 As explained in an earlier footnote, the required urea consumption can be calculated from the required NO_x reduction from engine-out to tailpipe.

23 "Depending on usage, a full tank of AdBlue® will run for several thousand miles and shouldn't need to be refilled between services." (Mercedes-Benz, 2018).

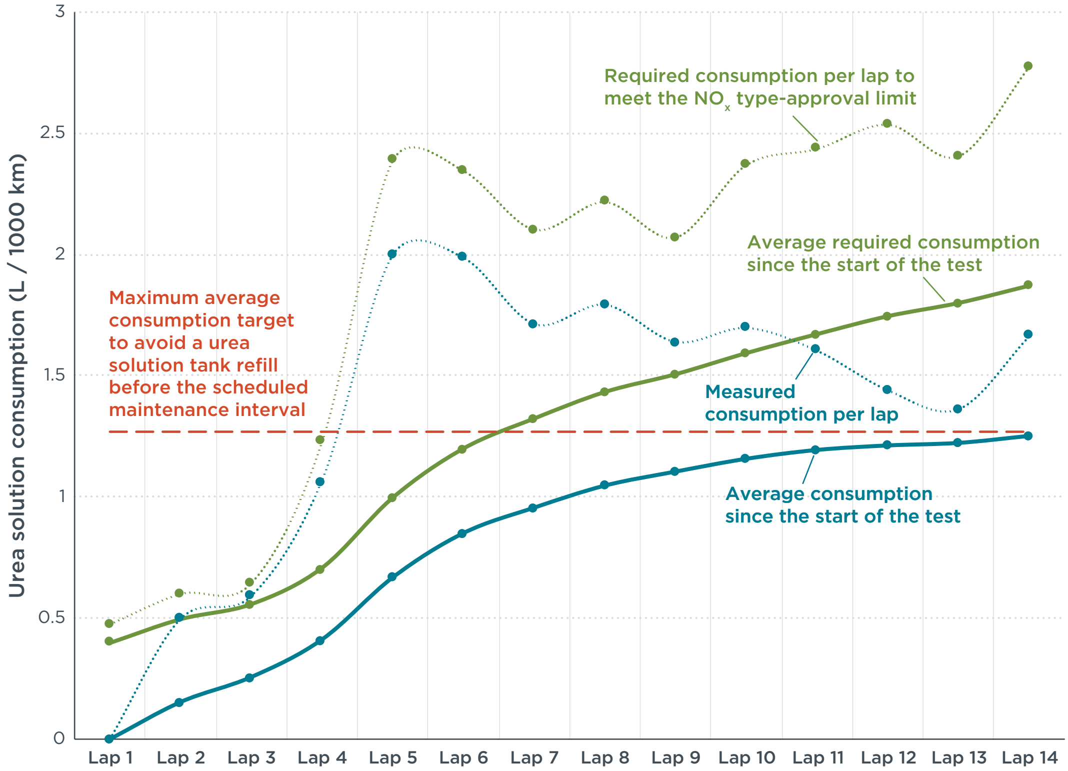


Figure 23: Urea solution consumption per 1,000 km estimated since start and per lap. The consumption per lap is increased from lap 3 along with engine-out emissions. But it is reduced from lap 10 even though test conditions and engine-out emissions are kept reasonably constant. The vehicle was driven 1.7 km before reaching the track.

SUMMARY OF POSSIBLE CALIBRATION STRATEGIES ON THE MERCEDES C200, BASED UPON STEP 4 TESTING

The on-road and on-track testing gave us some insights as to which defeat devices can potentially be ruled out and which ones are possibly being employed in the vehicle. As there were some instances of relatively low emissions during the RDE testing, it is unlikely that the vehicle is changing emissions strategy based on not being in the laboratory or on the exact vehicle speed profile. There is also no indication of a defeat device related to sensing the use of OBD or PEMS equipment. Another finding that supports the absence of a defeat device related to the exact NEDC speed profile is that we did not observe much difference between the first 4 km—the NEDC urban portion distance—of a cold-start urban driving test conducted on the road or track compared with the cold-start urban portion of the NEDC in the laboratory.

During the on-road and on-track testing we found that small changes in test protocol led to large changes in NO_x emissions, making it hard to get repeatable results. We also saw emissions increase outside urban-type driving and after repeated urban tests. In addition, we found strong evidence that emissions increased at lower ambient temperatures. Figure 24 shows engine-out and tailpipe NO_x emissions as a function of ambient temperature for all on-road tests. The figure shows how both engine-out and tailpipe emissions rose with decreasing ambient temperature. Note that all these tests occurred at ambient temperatures below 20°C—the lower bound of the temperature range permitted for the vehicle type-approval test.

Our testing of the Mercedes C200 found the following possible emissions control strategies:

» **EGR strategies.** There are most likely at least three EGR strategies—low EGR, medium EGR, and high EGR. From our testing, EGR rates above about 20% were seen only during the first three on-track urban laps, when the EGR rate was 36%–37% on laps 2 and 3. This would be high EGR, associated with NO_x emissions below compliance levels. After the length of the NEDC was reached, EGR rates dropped to about 20%, or medium EGR, for laps 5 to 12. This suggests a timer function. Our testing also suggests a second likely trigger to switch between medium and low EGR, or 5%–10% EGR rate, based on some measure of engine coolant temperature, as the EGR rate decrease is inversely proportional to the engine coolant temperature increase.

» **SCR strategies**. As we previously theorized, there are most likely at least two SCR urea injection strategies, one designed for high SCR NO_x conversion and one for low SCR NO_x conversion and low urea consumption. We observed absolute NO_x reduction and urea injection rate drops during both RDE and on-track tests while no measurable changes occurred in the test conditions. This leads us to propose the possibility of a time- or distance-based trigger that reduces urea injection once the usual distance driven during a type-approval test is reached. Another possibility is the use of a strategy that reduces urea consumption based on average trip consumption. Such a strategy could limit the urea consumption to a level compatible with the urea tank refill frequency that is scheduled at each vehicle's maintenance.

In summary, based on our on-road and on-track testing, there appear to be multiple emissions control strategies for EGR and SCR. Behavior of both was unpredictable and appeared to include triggers for high emissions. The calibration changes could be triggered by one or more of:

» EGR: ambient temperature, engine coolant temperature or similar, or timer.

» SCR: ambient temperature, timer, or maximum urea consumption. We were unable to find an explanation for the very low SCR conversion efficiency on Run 1 of the RDE testing.

The next step is to see what we can learn from laboratory testing.

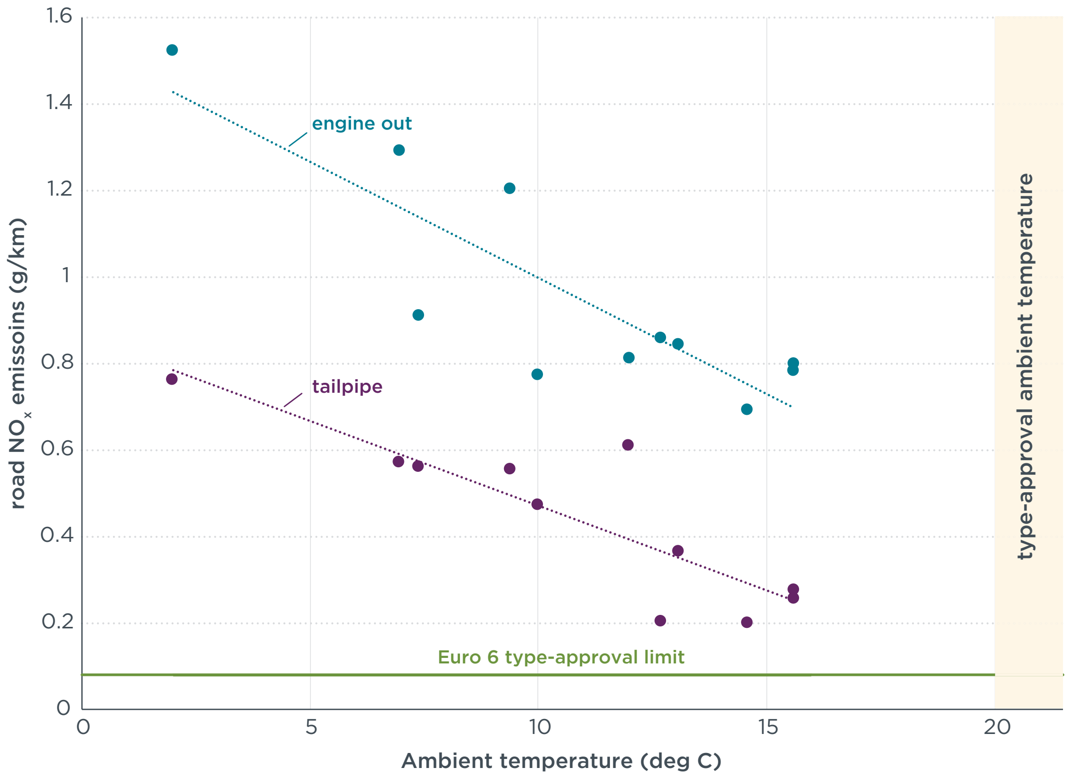


Figure 24: On-road NO_x engine-out and tailpipe emissions as a function of ambient temperature.

STEP 5: IN-DEPTH LABORATORY TESTING

Step 4 addressed the on-road/on-track component of the testing strategy to identify defeat devices. Step 5 starts at the other end with the laboratory testing and step-by-step gets close to mimicking real-world driving in the laboratory, as depicted in the laboratory testing flow chart (see Figure 25). As with Step 4, changing a small number of variables, ideally one, at a time is the best way to narrow down the cause and find the trigger for a defeat device, keeping in mind that one vehicle could have multiple defeat devices and multiple triggers. Repeat testing is also important for data integrity. If tests are not giving repeatable results, it could signal a defeat-device trigger. It is also beneficial to keep the test protocol flexible. If you see something strange, add tests and investigate.

Similar to the discussion in Step 4, this section is organized by the type of laboratory testing, with the discussion of each test type followed by examples from our testing of the Mercedes C180 and C200 vehicles.

TEST WITH CHANGES IN TEST CONDITIONS THAT SHOULD HAVE NO IMPACT ON EMISSIONS

The first step in the flow chart, the chassis dyno test under type-approval conditions, was covered by the testing performed as part of Step 2. The next laboratory testing step is designed to look for a switch type of defeat device. Each test in this section should be run very close to the type-approval test. The changes are only with respect to test preconditioning or vehicle setup—items that should not have any significant impact on emissions. Possible switch-related elements are as follows, although there could be additional items:

- **Dynamometer mode**. Because only the wheels on the drive axle rotate on a standard 2WD dynamometer, the ECU senses that two wheels are not turning. On some vehicles, especially with 4WD or AWD, this is treated as an error, and the ECU will not allow the vehicle to operate. In these cases, the vehicles must be put in a special dynamometer mode to run the laboratory test. The testing agency should note whether the vehicle requires a special dynamometer mode and should check for any changes in emissions. Changes can be identified either during on-road testing or with laboratory testing using a 4WD dynamometer.
- **Engaging reverse gear.** The standard protocol never makes use of the reverse gear, so gearbox sensors could be used to identify that an official test is being conducted if reverse is never engaged. Shifting the gearbox temporarily to reverse position when the vehicle is not moving should not have any impact on emissions.
- **Trunk/windows position.** During normal type-approval chassis tests, the trunk and windows are typically open. Closing the trunk and windows should not have any impact on emissions.
- **Seat belt.** During type-approval testing, the seat belt is not typically in use, except for vehicles equipped with stop/start technology, where there is a requirement that the seat belt be buckled during testing. Using the seat belt should not change emissions.
- **Steering wheel.** During type-approval chassis testing the steering wheel does not move. Turning the steering wheel should not affect emissions. Moving the steering wheel during a test on an RWD vehicle is possible, as only the rear wheels are engaged by the dynamometer. While the steering wheel cannot be moved during a dynamometer test of an FWD or AWD vehicles, it can be moved right before the wheels start spinning in the test. An effect on emissions from turning the steering wheel can also be looked for during on-road testing.
- **OBD.** An OBD monitor is typically plugged in during type-approval testing to collect OBD data. Being plugged into the OBD should not affect emissions.

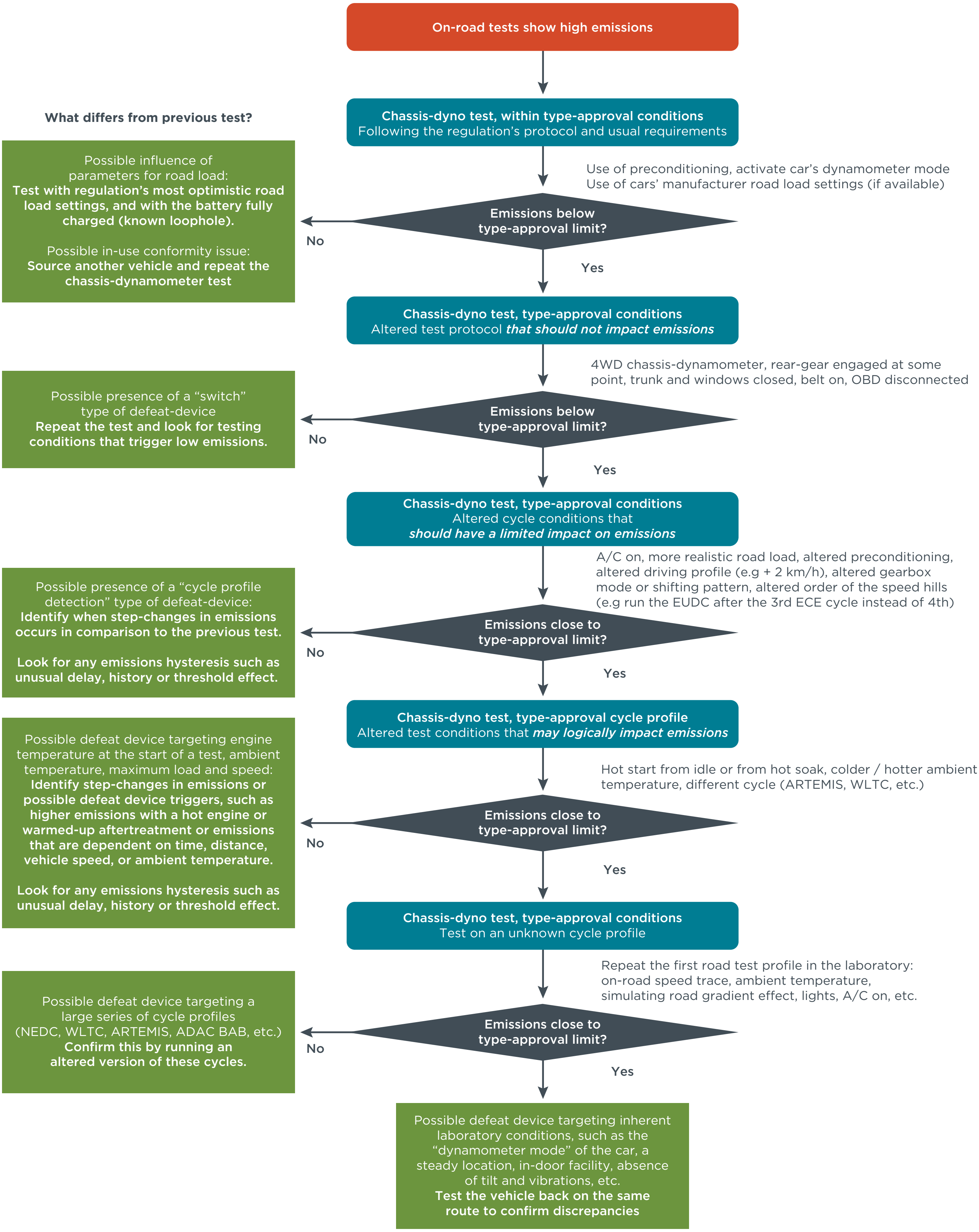


Figure 25: Laboratory step-by-step approach for defeat-device testing.

As a specific example of how this might work, we tested the Mercedes C200. To keep each trial close to the type-approval test, all of them were run using the NEDC test cycle with a cold start at an ambient temperature of 23°C. During our tests on the C200 we did not have access to a 4WD dynamometer, but we did vary all of the other listed parameters. To save time, we combined many of these test parameters into a single test (Table 7). If emissions changed, we would have followed up with testing on individual parameters.

We did not discover any defeat devices of the switch type on the C200. NO_x emissions stayed below the Euro 6 limit for every trial (see Figure 26). Results are detailed in Table 22 in Appendix E.

Table 7: Laboratory tests aiming to detect switch-type defeat device.

Test #	Vehicle	Test Description	Tailpipe NO_x CVS (g/km)
A1	C180	Type-approval test	0.069
B1	C200	Type-approval test with OBD connected	0.068
B2	C200	Reverse gear engaged before start Rear hatch closed Steering wheel movement before start Seat belt of the driver buckled OBD disconnected No modal measurement	0.077
B3	C200	Type-approval test with OBD disconnected	0.062

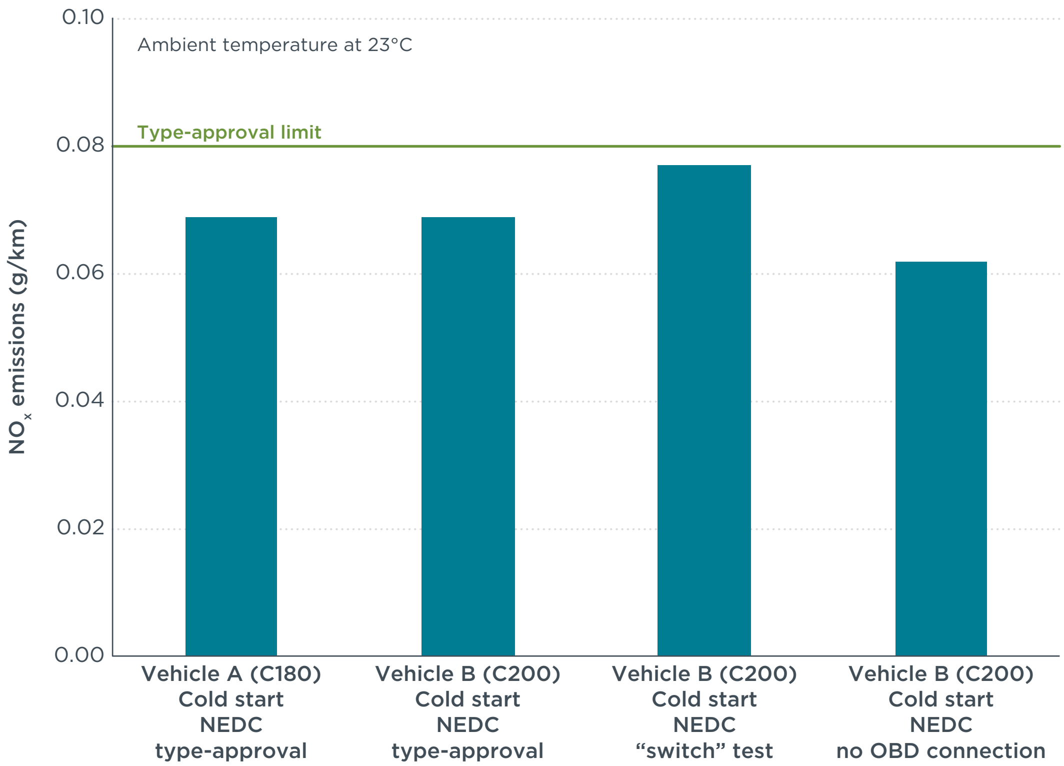


Figure 26: Laboratory tests aiming to detect a switch-type defeat device.

TEST WITH CHANGES IN TEST CONDITIONS THAT SHOULD HAVE LIMITED IMPACT ON EMISSIONS

The next laboratory testing step is to make minor changes to the testing procedure that should have only small if any effects on emissions—certainly much less than a 50% increase in NO_x emissions. The testing is still conducted using a cold start and the regular ambient temperature. Possible changes are to use real road load, no set preconditioning methodology, slightly increase the NEDC speed profile or change the order of some of the speed hills after the cold start, alter gearbox or shifting pattern, or turn the air conditioning on. Specific suggestions are:

» **Road load settings.** It is well documented that manufacturers use unrealistically low dynamometer road load settings as a way of obtaining better CO_2 type-approval results (Kühlwein, 2016). These settings come from either coast-down tests or are the output of tables from the regulation, also known as the "cook book," which depends mainly on vehicle mass.[24] Use of more realistic road load settings means that the engine will have to run at slightly higher load over the same speed trace. This should primarily affect fuel consumption and CO_2 and should not significantly impact NO_x emissions.

» **Preconditioning.** Type-approval testing requires a preconditioning of the vehicle before testing. This is conducted by running the Extra Urban Driving Cycle (EUDC), or the high speed portion of NEDC, three times and it is intended to ensure that the engine and aftertreatment system start from the same state each time. Bypassing or changing the preconditioning protocol might have some small impact on emissions immediately after the vehicle start, but there is no technical reason for a major emissions impact over the whole test. Further, any impact would affect the emissions only at the beginning of the test, which can be evaluated using second-by-second results.

» **NEDC speed profile.** A small alteration of the NEDC or the WLTC—for example by either increasing the speed a nominal amount or changing the order of the speed hills—should have very little emissions impact from a technical perspective. Increasing the vehicle speed by a small amount, such as 2 km per hour, would have some impact on load, but the emissions impact per kilometer should be minimal.

» **Air conditioning.** Turning the AC on is similar to using real road-load settings in that it increases the engine load by a certain amount. On average, using AC will increase engine load by 5%–10%. While this could certainly have an impact on CO_2 emissions, only a small effect on NO_x emissions would be expected. Note that in the United States, the EPA found a defeat device tied to AC operation installed on almost half a million 1992–1995 GM Cadillacs (Myers, 1995).

» **Gearbox or shifting pattern.** There is no technical reason why changing the shifting pattern—for example by keeping fifth gear engaged instead of shifting into sixth on the final EUDC step—should have a significant impact on NO_x. While the engine will run in a different part of the engine map, the power demand would still be the same, and emissions should not be significantly altered.

During testing on our example Mercedes C200, we varied three of these parameters —road load, AC in "auto" mode, and altered preconditioning. See Table 8 for the test descriptions, the engine-out, and tailpipe NO_x results for each test, and Table 9 for a summary of some additional key results. More detailed results can be found in Table 23 in Appendix E.

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24 Simulated inertia and dyno loading requirements are defined in table A4a/3 of the UNECE Regulation No. 83 (UNECE, 2015).

- **Realistic road load**. The Mercedes C200 was a somewhat unique case, where the "real" road load actually was lower above 40 km/hour than the default "cook book" road load. That is most likely because the C-Class is among the best in class for aerodynamics characteristics, which play a major role at higher speeds (Clark, 2013). It is not surprising that using the real road load instead of the "cook book" did not impact emissions because it did not cause higher load. NO_x emissions remained below the Euro 6 limit. We could not confirm which road load parameters were used by the manufacturer for type approval. We opted to use the "real" road load for all the laboratory tests except for the specific test B0 in Table 8.
- **AC on.** Repeating the type-approval test with the AC on default "auto" mode set at 21°C did have an impact on emissions, increasing the average tailpipe NO_x emissions by 80% from the case where AC was off, and about 50% above the type-approval limit. Increased emissions occurred during the first three minutes of the cold-start test and during the highest-load, EUDC part of the cycle. It appears the cause of the higher emissions was an increase of engine-out NO_x due to a reduction of the EGR rate in these portions of the test. This certainly suggests an improper calibration, although it is not clear whether it is a defeat device based upon air conditioning use or is due to an emissions control system design that does not control emissions outside of the narrow window of the NEDC. It certainly suggests that AC operation is important to include in official type-approval testing, as is already done in the United States, to ensure low emissions when AC is in use.
- **Altered preconditioning.** Instead of the standard 3xEUDC performed before the vehicle soak, we performed steady-state operation at a handful of speeds for 10 minutes each and then allowed the vehicle to soak overnight as normal. Upon testing, in the first part of the NEDC—the lower-speed ECE portion—the vehicle behaved similarly to performance in the type-approval test. But during the higher-speed EUDC portion, the vehicle switched to high NO_x engine-out emissions and low NO_x conversion from the SCR, ultimately leading to a NO_x emissions result approximately five times higher than the type-approval value. It should be noted that we ruled out the possibility of DPF regeneration as the cause of this behavior. This observed behavior strongly suggests that a defeat device has been triggered and is deserving of further investigation to identify the cause. However, we were not able to repeat this particular test because of chassis-dynamometer unavailability.

Table 8: Description of laboratory tests that should have a limited impact on emissions.

Test #	Vehicle	Test Description	Tailpipe NO_x CVS (g/km)
B0	C200	Type approval test + "cook book" road load	0.064
B1	C200	Type approval test + "real" road load	0.068
B4	C200	AC on + "real" road load	0.122
B5	C200	Altered preconditioning + "real" road load	0.408

Table 9: Results of laboratory tests with "real" road load, AC on, and altered preconditioning (vehicle C200).

TEST	B1	B4	B5
Engine-out NO_x modal (mg/km)	161	374	556
Tailpipe NO_x modal (mg/km)	69	106	376
Tailpipe CO_2 CVS (g/km)	140	183	140
Average SCR NO_x conversion (%)	57	72	32
Estimated EGR rate	26	18	18
Ratio to Euro 6 limit (NOx conformity factor)	0.86	1.33	4.70
Average ambient temp (°C)	23.8	22.8	24.1

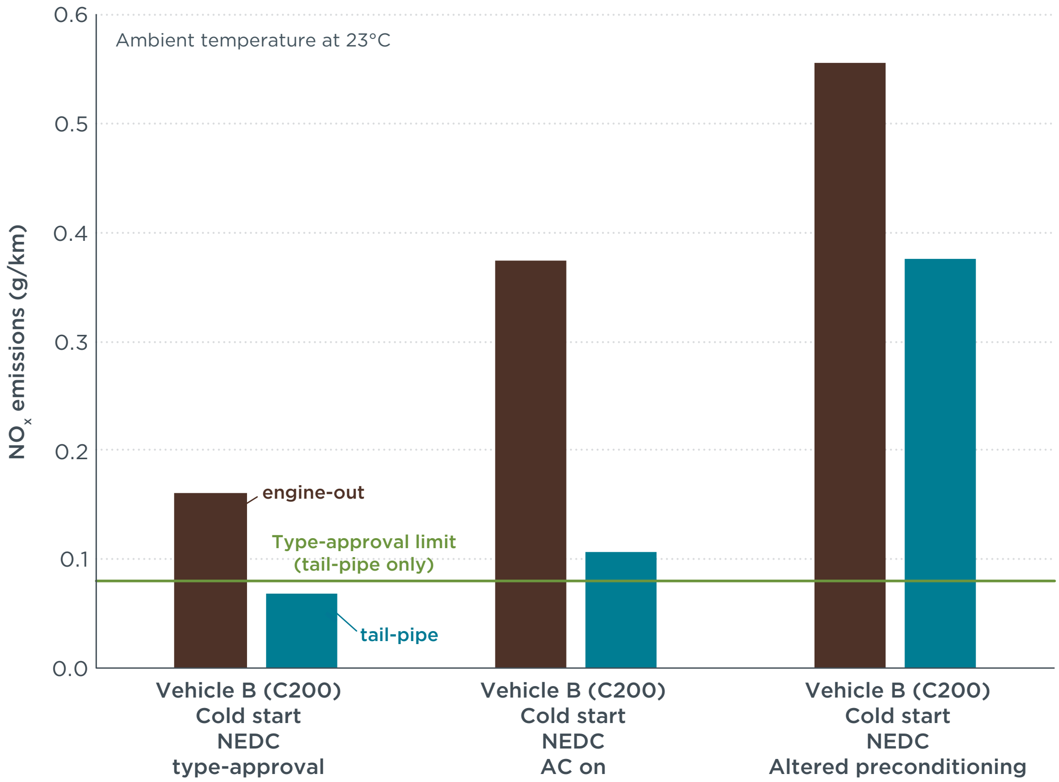

Figure 27: Laboratory test results that should have a limited impact on emissions.

TEST WITH CHANGES IN TEST CONDITIONS THAT MAY HAVE A LOGICAL IMPACT ON EMISSIONS

The next laboratory testing step is to evaluate factors with larger potential impacts on emissions, such as ambient temperature, hot engine start, and other duty cycles. Note that although these test conditions could potentially have a somewhat significant effect on emissions in certain cases, such an impact should be predictable and logical based on a technical understanding of the operation of the emissions control system.[25] So, in these tests, one should pay less attention to absolute emissions and more to the overall behavior of the system. Because of the larger potential impacts, it is important to stick to one variable at a time. Let's take these one by one.

25 Note that the expected emissions impact can be negative, such as for hot starts where emissions should be lower than after cold starts.

1. AMBIENT TEMPERATURE

Ambient temperature alone should never trigger a change in emissions calibrations. For example, it is reasonable that EGR would need to be reduced at lower intake manifold temperatures to avoid condensation and protect the system, but there are other factors that affect intake manifold temperature besides ambient temperature, such as heating up of the engine, exhaust gas temperature, and intake air flow rate. Emissions should increase only modestly outside the type-approval window. For example, for temperatures common in Europe the impact of ambient temperature should not lead to NO_x emissions more than 1.5 times the type-approval limit (European Commission, 2017c).

During testing on our example Mercedes C180 and C200, we conducted NEDC cold-start tests at ambient temperatures of 0°C, 12°C, and 14°C. Test descriptions and tailpipe NO_x emissions results are in Table 10, and engine-out and tailpipe emissions are shown in Figure 28. More-detailed results are shown in Table 24 in Appendix E. Note that for testing of the C180, the vehicle was not fully instrumented and is therefore missing some key information, such as engine-out NO_x. We can see, however, that tailpipe emissions increased substantially between 14°C and 12°C, in line with results found during the on-road RDE testing described in Step 4. Because of the lack of engine-out data, it is not possible to determine from this set of tests whether the increase in tailpipe NO_x was due primarily to a reduction in EGR rate, or urea injection rate, or both.

Table 10: Test description of laboratory tests with lower ambient temperature.

Test #	Vehicle	Test Description	Tailpipe NO_x CVS (g/km)
B1	C200	Type-approval test (for reference), Cold start NEDC at 23°C	0.068
B6	C200	Cold start NEDC at 14°C	0.052
A2	C180	Cold start NEDC at 12°C	0.389
A3	C180	Cold start NEDC at 0°C	0.262

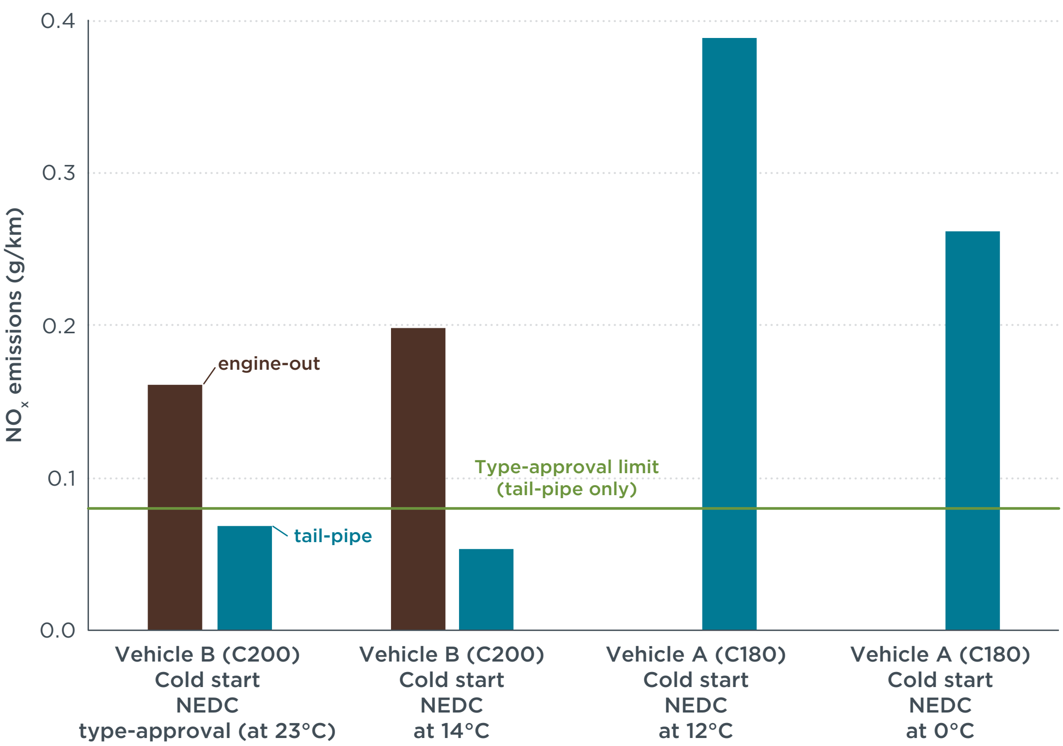

Figure 28: NO_x emissions from laboratory tests with lower ambient temperature. Engine-out emissions are not available for vehicle A because of unavailable instrumentation.

2. HOT ENGINE START

There is no logical technical justification for any change in emissions control system calibration based on starting the test after an idle or after a restart with the engine already warmed up, commonly called a hot start, instead of a cold start. NO_x emissions are easier to control when everything is warmed up. Improved combustion stability with a warm engine allows the use of higher EGR rates, and SCR aftertreatment performs much better at higher catalyst temperatures. Logically emissions should decrease when starting the NEDC with a warmed-up engine. NO_x hot-start emissions from diesels in the United States are only 15% of cold-start emissions because of these effects (see Figure 1).

We performed several type-approval tests on our example Mercedes C180 and C200 with the engine already warmed up. The tests differed in how long the vehicle was shut off before starting the trial. Test descriptions are shown in Table 11; tailpipe NO_x emissions results are shown in Figure 29; and a summary of additional results is shown in Table 12. A more-detailed summary can be found in Table 25 in Appendix E. The testing conditions between the two vehicles differed only in the duration for which the ignition was off before the test. The C200 was restarted more than 30 minutes after the end of the previous trial and was also tested without shutting the engine off following the previous test. The C180 was restarted less than 20 minutes after the end of the previous trial. Testing of the C200 did show slightly lower emissions with the hot restart after the longer engine shutoff. However, testing on the C200 without shutting off the engine and the C180 hot restart after the shorter engine shutoff both had emissions increases of more than five times that of the hot restart on the C200. This increase is in line with what we saw on the track testing, where repeating the urban laps 14 times in a row resulted in a large emissions increase.

Interestingly, emissions control strategies on the C200 were completely different after a hot restart and after an idle. Following the hot restart, engine-out NO_x emissions tripled compared with a cold-start test, but this was offset by a large increase in the efficiency of NO_x conversion in the SCR catalyst. This indicates that the SCR catalyst was up to operating temperature and able to convert at very high efficiency even after an engine shutoff of more than 30 minutes. After an idle, engine-out NO_x remained relatively unchanged compared with the hot restart test, or about triple compared with a cold start. However, NO_x conversion in the SCR catalyst dropped dramatically from 94% to 67%, leading to the five-times increase in tailpipe emissions. While it is possible that the exhaust flow at idle cooled down the SCR catalyst more than the 30–45 minute soak, note that the C180 with only a 10–20 minute soak also had tailpipe emissions more than five times higher than the C200 with the 30–45 minute soak, suggesting that SCR catalyst cooldown is not the problem.[26]

These results are inconsistent and do not appear to conform with expected behavior, indicating several possible defeat device triggers. Results suggest that NO_x engine-out emissions are high when the engine is warmed up because of a reduced EGR rate, signaling a possible defeat device based on some measure of engine coolant or intake air temperature at the start of the test. Also, the urea injection rate and subsequent SCR efficiency may be time-dependent.

26 These results support the importance of proper instrumentation. Our inlet SCR temperature sensor, which would have told us the SCR catalyst temperatures, did not arrive in time for these tests. And we did not install an engine-out NO_x sensor on the C180.

Table 11: Laboratory tests from hot-start, engine idling, or ignition off with different soaking times. Numbers given for tailpipe NO_x correlate with the detailed vehicle results presented in Table 12.

Test #	Vehicle	Test Description	Tailpipe NO_x (from CVS) (g/km)
B1	C200	Type-approval test (for reference)	0.068
B7	C200	Engine start warm (coolant >70°C), start test from engine off between 30-45 minutes after previous test (4 tests)	0.038 (min/max – 0.034/0.041)
B8	C200	Engine start warm (coolant >70°C), start test from engine idle (2 tests)	0.202 (min/max – 0.202/0.210)
A1	C180	Type-approval test (for reference)	0.069
A4	C180	Engine start warm (coolant >70°C), from engine off between 10–20 minutes after previous test (5 tests)	0.214 (min/max – 0.168/0.271)

Table 12: Results of laboratory tests with hot start, starting from engine idling, or ignition off with different soaking times. Cells left blank represent data we did not obtain.

TEST	B1	B7	B8	A1	A4
Engine-out NO_x modal (mg/km)	161	536	577	-	-
Tailpipe NO_x modal (mg/km)	69	32	193	-	-
Tailpipe NO_x CVS (mg/km)	68	38	202	69	214
Tailpipe CO_2 CVS (g/km)	140	131	127	136	126
Average SCR NO_x conversion (%)	57	94	67	-	-
Estimated EGR rate (%)	26	-	16	-	-
Average coolant temp (°C)	58	-	88	-	-
Ratio to Euro 6 limit (NO_x conformity factor)	0.86	0.40	2.41	0.86	2.68
Average ambient temp (°C)	23.8	25.0	24.1	23.0	23.0

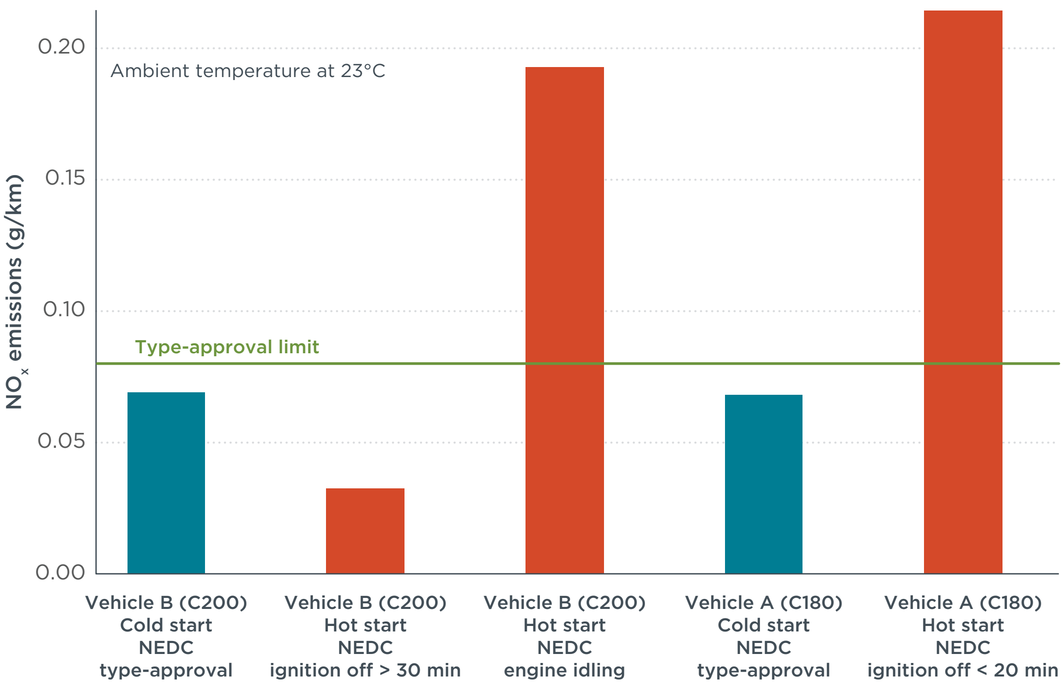

Figure 29: Laboratory tests from hot start, engine idling, or ignition off with a longer (30–45 minute) soak time for vehicle B than for Vehicle A (10-20 minutes).

3. DUTY CYCLES

Different cycles can change emissions because of different loads on the engine, but the emissions control system calibrations should not change for a given engine speed and load. To examine the impacts of a test cycle different from the NEDC, we selected the Artemis urban cycle, as it is somewhat similar to the ECE portion of the NEDC. Table 13 shows some key characteristics of the Artemis urban versus NEDC urban section, which is made up of four ECE cycles repeated without interruption. They are close in terms of average distance driven, duration, percentage of idle, and top speed. The primary difference is higher average accelerations and less steady-state driving for the Artemis urban cycle. This means the Artemis is a more transient cycle, which might lead to higher emissions if the engine and aftertreatment system were not designed for transient operation.

Table 13: Comparison of main characteristics between the urban part of the NEDC and the Artemis urban test cycle.

	NEDC urban (ECEx4)	Artemis Urban
Average speed / max speed (km/h)	18.4 / 50	17.6 / 58
Average positive acceleration / Max acceleration (m/s^2)	0.64 / 1.05	0.73 / 2.86
Distance (km) / Duration (s)	4 / 780	4.5 / 920
Idle (%)	30	29

We performed a cold-start Artemis urban test on our C180 and C200. Table 14 compares C200 results on the urban portion of the type-approval test NEDC (B1) with Artemis urban tests on the C200 (B9) and the C180 (A5), all using cold starts. It can be seen that NO_x emissions per kilometer tripled on both vehicles. Table 15 contains a summary of additional test details. Additional data can be found in Table 26 in Appendix E. Note that in comparison of the NEDC urban portion with the Artemis urban segment, estimated average EGR rate decreases from 28% to 20% and average SCR conversion drops from 36% to 21%, resulting in the threefold increase in NO_x emissions observed.

Table 14: Laboratory tests using the Artemis urban cycle.

Test #	Vehicle	Test Description	Tailpipe NO_x CVS (g/km)
B1 urban only	C200	Urban portion of type-approval (cold start NEDC)	0.133
B9	C200	Artemis urban (cold start)	0.399
A5	C180	Artemis urban (cold start)	0.469

Table 15: Results of laboratory tests with urban NEDC and urban Artemis cycle. Cells left blank represent data we did not obtain for that test.

TEST	B1 urban only	B9	A5
Engine-out NO_x modal (mg/km)	208	506	-
Tailpipe NO_x modal (mg/km)	133	399	-
Tailpipe NO_x CVS (mg/km)	130	400	469
Tailpipe CO_2 CVS (g/km)	169	247	251
Average SCR NO_x conversion (%)	36	21	-
Estimated EGR rate (%)	28	20	-
Ratio to Euro 6 limit (NO_x conformity factor)	1.66	4.99	5.86
Average ambient temp (°C)	23	23	23

To help identify the source of the NO_x emissions increase from the NEDC urban to the Artemis urban cycle, Figure 30 compares engine operating conditions and NO_x emissions over the two cycles on vehicle C200. The left part of Figure 30 indicates the NO_x emissions levels over the range of engine speed and load points covered over the NEDC urban portion of the cycle. It can be seen that NO_x emissions under the NEDC urban test are mostly low, less than 0.0025 g/s. The right part of Figure 30 shows the same information but for the Artemis urban cycle. It can be seen that, as expected, the Artemis urban covers a wider engine operating range than the NEDC urban with higher engine speeds and loads. There are two interesting things to note. First is how rapidly the NO_x emissions rate increases once the engine is operating outside the range covered by the NEDC urban. NO_x emissions reach more than 0.0200 g/s for some of these operating points. The magnitude of the NO_x emissions increase outside the NEDC operating points is far higher than the CO_2 emissions increase because of higher power demand at those operating points. As discussed earlier, this is most likely a case of an emissions control system not designed or calibrated to control emissions outside the boundary conditions of the tests. As previously mentioned, this would most likely be considered an illegal defeat device in the United States, but it is not clear that this would be considered an illegal defeat device in the European Union. Second, note that even within the NEDC urban operation area, there were far more events with emissions above 0.0025 g/s and also a significant number of events with emissions above 0.0100 g/s, suggesting there may also be a calibration trigger based upon recognition of the NEDC operating range.

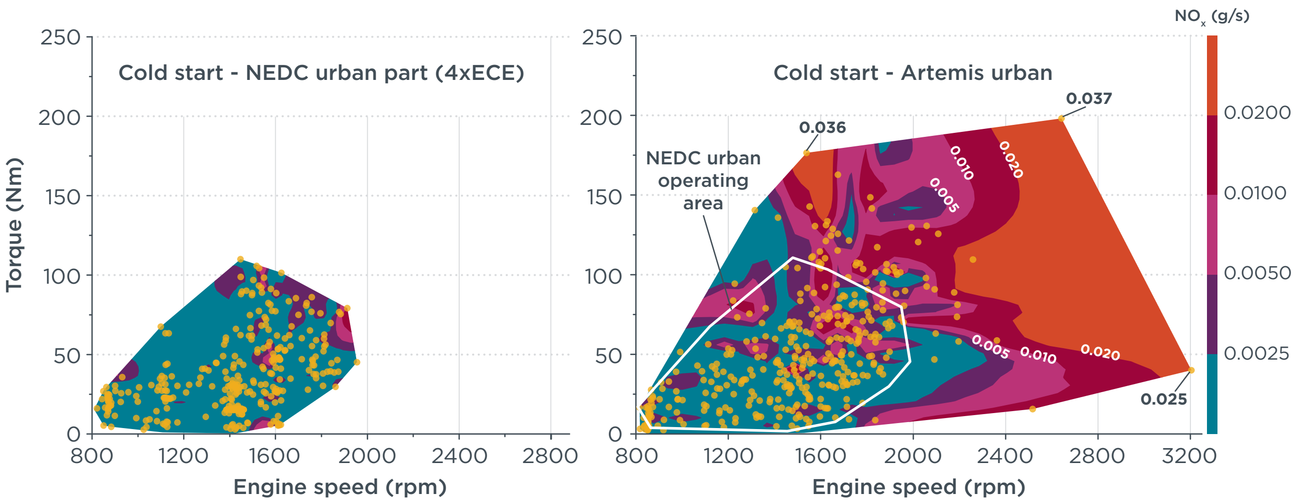

Figure 30: Map of NO_x emissions rate tailpipe (g/s) for the cold-start urban portion of the NEDC type-approval test (left), and for the cold-start Artemis urban test on vehicle C200.

'REAL-WORLD' DRIVING IN THE LABORATORY

Running the exact speed and grade trace on the dynamometer that was driven during real-world testing in Steps 2 or 4 is an excellent way to help identify possible defeat devices that behave differently in the laboratory and on the road. However, we were not able to perform this test on the example vehicles, as the laboratory was not equipped with a fully customizable vehicle trace and a grade simulator.

ADDITIONAL LABORATORY TESTS

As noted in our flow charts for laboratory and on-road testing, flexibility should be maintained and additional testing conducted when the results are contradictory or confusing. For example, we decided to conduct additional laboratory tests combining various conditions that we suspected led to elevated emissions—hot start, lower ambient temperatures, and Artemis urban cycle. Test descriptions and tailpipe NO_x emissions are shown in Table 16, including the results for the NEDC urban portion and Artemis cold-start tests A5 and B9 for comparison. The tailpipe NO_x emissions results on vehicle C180 are compared in Figure 31. As discussed in the previous section on duty cycles, NO_x emissions approximately tripled when going from the NEDC urban to the Artemis urban cycle while still maintaining a cold-start condition and 23°C ambient temperature. With the addition of a hot-start condition at 23°C, emissions increased 80%. Conducting the test at lower ambient temperatures caused incremental increases of 57% at 12°C and 102% at 0°C compared with the hot start at 23°C. These results are consistent with the theory that multiple defeat device strategies exist that are triggered based on engine temperature, engine load, and ambient temperature. The results also support the idea that the impact on emissions can be compounded when multiple defeat devices are triggered.

Table 16: Laboratory tests using the alternative Artemis urban cycle compared with the urban part of the NEDC.

Test #	Vehicle	Test Description	Tailpipe NO_x CVS (g/km)
B1 urban only	C200	Urban portion of type-approval (cold start NEDC)	0.133
A1 urban only	C180	Urban portion of type-approval (cold start NEDC)	0.118
B9	C200	Artemis urban (cold start) at 23°C	0.400
A5	C180	Artemis urban (cold start) at 23°C	0.469
A6	C180	Artemis urban (hot start) at 23°C	0.790
A7	C180	Artemis urban (hot start) at 12°C	1.243
A8	C180	Artemis urban (hot start) at 0°C	1.596

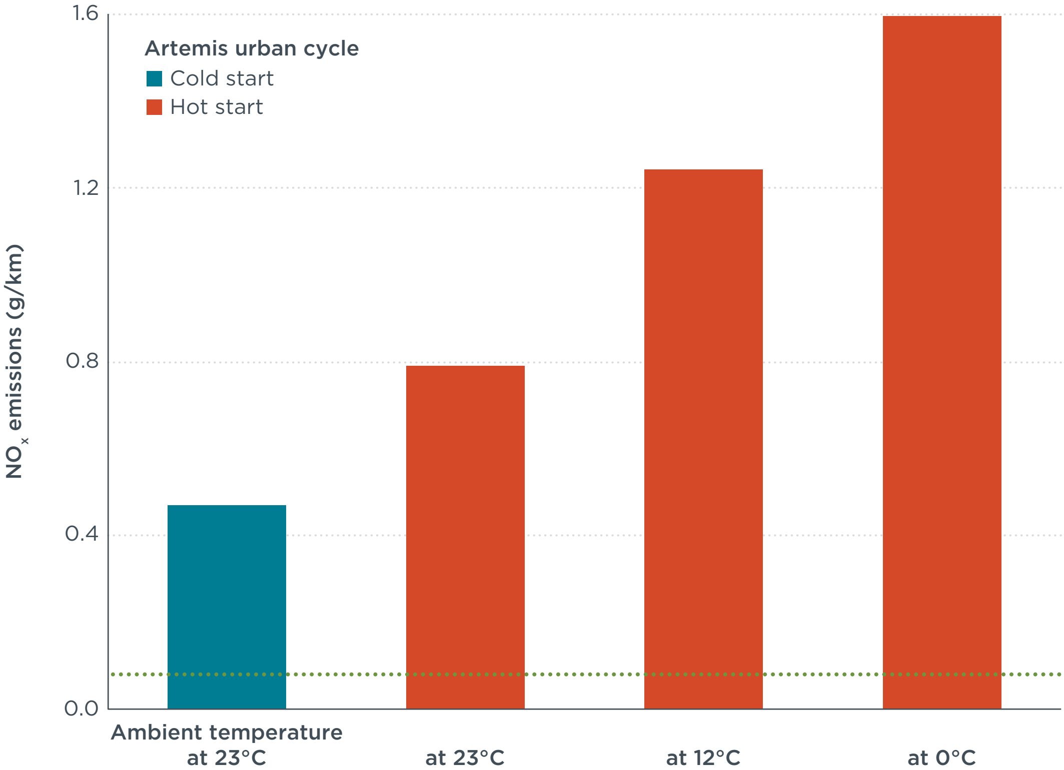

Figure 31: Laboratory tests using the alternative Artemis urban cycle. Emissions increase from a hot start and with lower ambient temperature (vehicle Mercedes Benz C180). More details can be found in Table 27 in Appendix E.

SUMMARY OF CHASSIS DYNAMOMETER TESTS

The different dynamometer tests revealed how the vehicles' emissions behavior responded to changes in the test protocol. NO_x emissions increased substantially with the AC on as well as during more-transient testing such as the Artemis urban cycle when the engine was outside its usual operating area of the NEDC type-approval test. As previously discussed, this behavior may not currently be considered an illegal defeat device in the European Union, but it is nonetheless problematic.

Engine-out NO_x emissions consistently increased when the engine was warmed up, reinforcing our theory that there is an EGR strategy that reduces EGR rate once the engine is fully warmed up.[27] We also observed SCR conversion behaving unpredictably under different types of hot-start conditions. The SCR conversion seemed to be more related to how long the ignition had been turned off rather than the actual temperature of the engine. In other words, the results suggest that the time after engine start has an influence on urea injection strategy and SCR conversion efficiency.

The dynamometer testing conducted at lower ambient temperatures supported findings from the on-road testing that there is a calibration change and large emissions increase between 14°C and 10°C. The results support our theory that both SCR and EGR strategy are affected by this calibration change.

The test with an altered preconditioning protocol show an unexplained increase in engine-out NO_x emissions as well as reduced urea injection or SCR efficiency. Recall that we were not be able to investigate any further details of this observation.

27 Reduced EGR rates could be acceptable if they were compensated with higher SCR conversion efficiency, but this was seen only on a single test after a 30–45 minutes engine shutoff on the C200. In all other testing, reduced EGR rates led to large increases in NO_x emissions.

STEP 6: SUMMARIZE DATA ANALYSES

After testing is complete, it is important to analyze and summarize the results. On the example Mercedes test, both the on-road and the laboratory testing showed many instances of behavior that is difficult to explain from a technical perspective, both for EGR and SCR emissions control.

To look for possible defeat-device triggers, it is possible to plot data in a form that would display whether well-understood emissions control functionality is present. For example, it is well known that SCR efficiency has a strong dependence on catalyst temperature. The expected behavior of an SCR system would be that NO_x conversion over the SCR would increase with rising catalyst temperature, lighting off around 200°C.[28] Above these temperatures, conversion should be more than 80% with a possible drop in efficiency at very high temperatures exceeding 450°C. Figure 32 shows the average SCR conversion efficiency as a function of inlet SCR temperature for all tests from which we able to calculate SCR conversion. The figure shows that similar catalyst temperatures led to NO_x conversion ranging from 20%–80%. Thus, the low SCR catalyst efficiency found on many tests was not due to low or high catalyst temperatures.

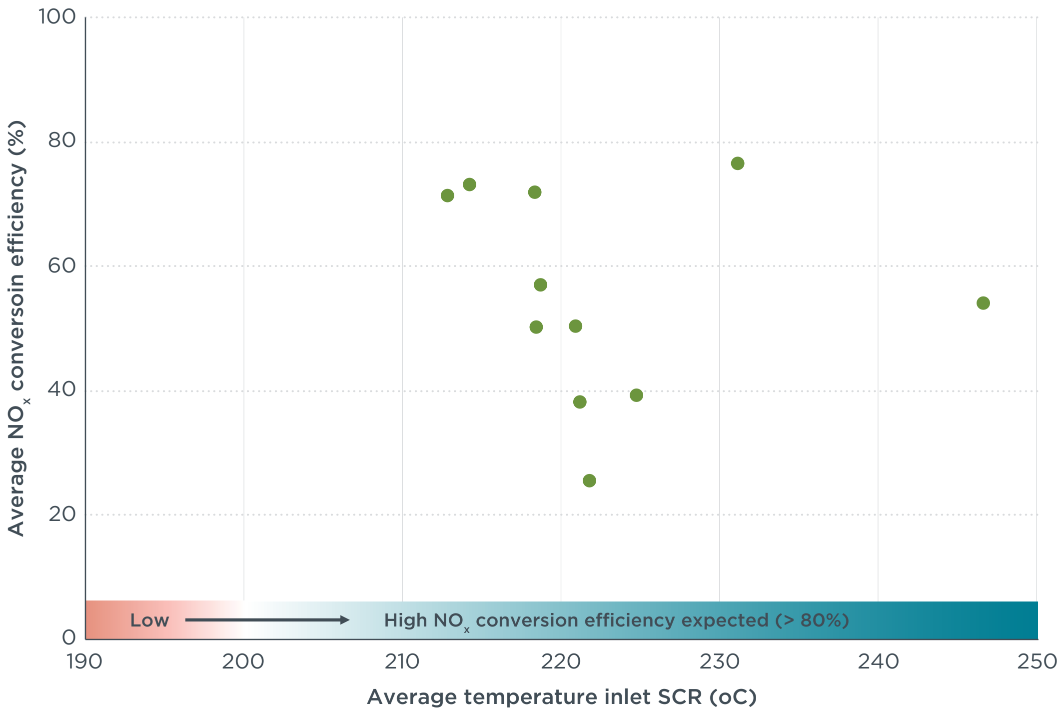

Figure 32: On-road SCR NO_x conversion efficiency and SCR inlet temperature compared with expected operation at high efficiency on vehicle C200.

Figure 33 shows engine-out NO_x emissions and average EGR rate for the different NEDC tests performed in the laboratory on the Mercedes C200. As expected, high engine-out NO_x emissions occur when a lower EGR rate is used. More interestingly, we can identify that a lower EGR rate strategy is used because of at least three likely triggers, when:

» The engine is started hot. In this case, EGR rates decrease and engine-out NO_x emissions increase with the higher engine temperature. This is the inverse of what would be expected. Typically, EGR rates might need to be decreased at lower engine temperatures for fear of condensation of corrosive compounds in the EGR

28 The urea solution also needs around 200°C to vaporize into gaseous ammonia.

system. But in the case of the presented testing, nothing explains the need to reduce EGR for the protection of the engine.[29]

» The AC is on. The additional load on the engine due to the AC is expected to lead to higher emissions. But there is no logical explanation why the EGR rate cannot be maintained at the same level to help contain engine-out NO_x emissions.

» The preconditioning was altered by using steady-state operation at a handful of speeds for 10 minutes each instead of the standard three repetitions of the EUDC. As discussed, the sudden switch to reduced EGR rate during the higher-speed EUDC portion at the end of the test cycle remains unexplained.

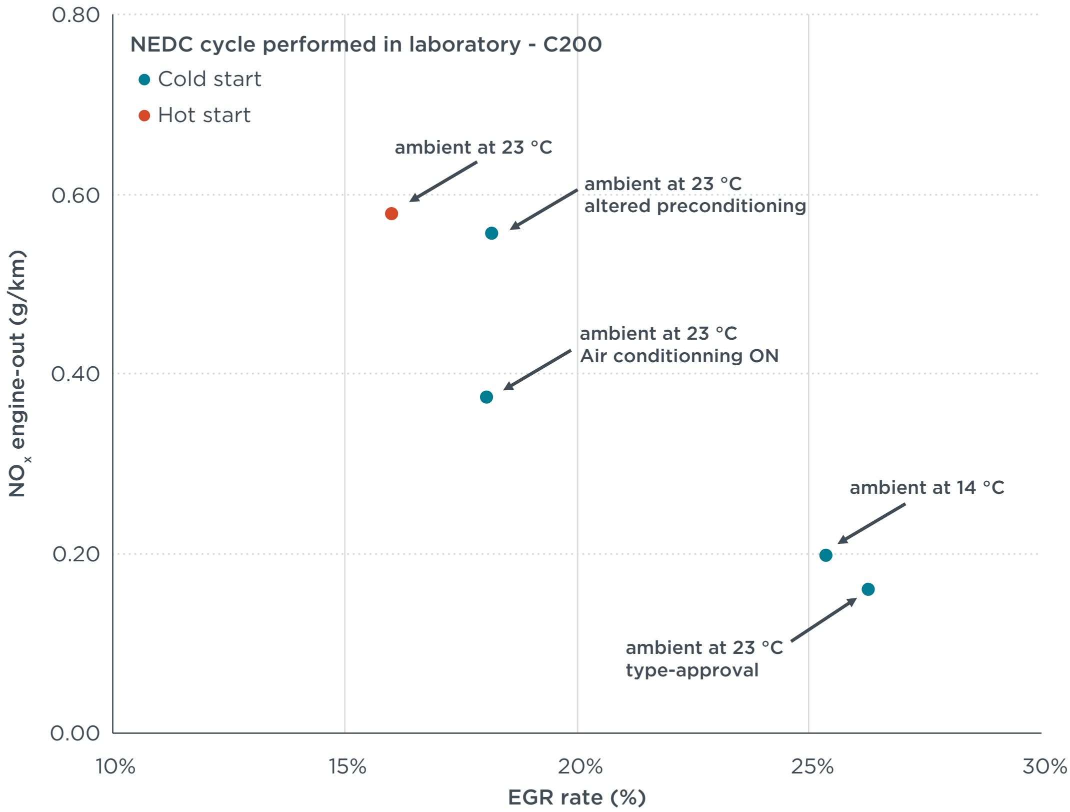

Figure 33: NO_x engine-out emissions and average EGR rate for different NEDC laboratory tests on vehicle C200.

As we have shown, the emissions control strategy of the Mercedes C180 and C200 displayed calibration changes and emission triggers that cannot be explained from a technical standpoint. Our testing shows that multiple defeat devices are most likely being employed to optimize NO_x emissions control under type-approval testing conditions and reduce emissions control effectiveness in real-world driving. We have categorized the potential defeat devices, all of which would likely be considered illegal based on U.S. regulatory guidance, as follows:

29 It is also possible that EGR rates would need to be decreased at high engine coolant temperature (above 105°C), high ambient temperature (above 40°C) or at high altitude (above 1,500m). However, none of these conditions were present on any of our testing.

- Reduced EGR based on ambient temperature, around 12°C.
- Reduced EGR based on engine temperature or similar measure like coolant or intake manifold temperature.
- Reduced SCR efficiency based on ambient temperature, around 12°C.
- Reduced SCR efficiency based on a function of either time, distance, or average urea consumption since engine-on.

Testing also showed reduced EGR and SCR efficiency that is possibly related to altering the vehicle's preconditioning before testing. However, we were unable to conduct additional testing to further investigate the existence of such a defeat device or understand how it might function.

Our testing also uncovered the presence of possible design limitations on the emissions control system of the Mercedes C200, limiting the maximum EGR rate during more transient and higher engine speed and load operation. Provisions for drivability and engine and emissions control system protection are enforced differently in Europe and the United States. These calibration and emission changes would most likely be considered illegal defeat devices under U.S. requirements but not in Europe without questioning the robustness of the engine and aftertreatment design, such as EGR cooler size.

It is also important to understand how the presence of multiple defeat devices and design limitations may result in even higher emissions when their effects are compounded. Figure 34 illustrates how, under type-approval conditions, NO_x emissions are very low, as can be seen on the left-end bar. Going from left to right across the figure, as multiple defeat devices and design limitations are activated—including hot start, lower ambient temperatures, and different duty cycles—NO_x emissions may increase more than 20-fold.[30] None of the conditions represented in this chart are extreme by any measure. The lowest ambient temperature represented is 0°C, which is not unusual for many parts of Europe. The driving cycles are representative, and there is nothing unusual about driving a vehicle whose engine has been warmed up.

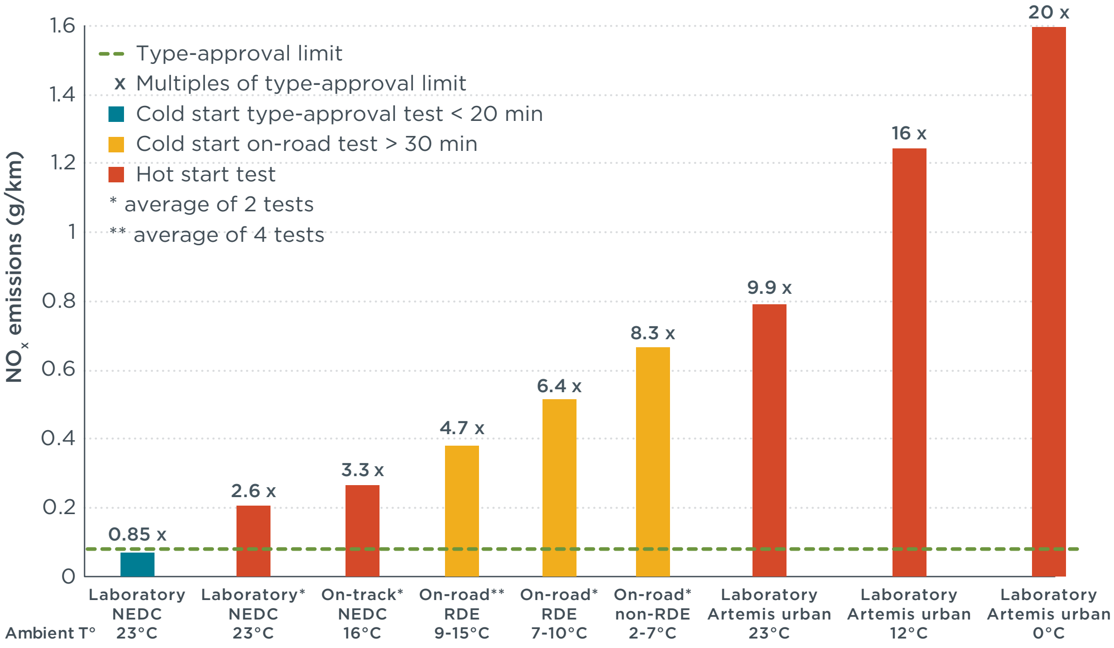

Figure 34: Summary of type-approval test results and key testing conditions that led to elevated NO_x emissions on the Mercedes C200 (first five tests) and C180 (last four tests).

30 The duration of the cold-start tests is identified in Figure 34 because longer cold-start tests should have lower emissions with engine and aftertreatment warmup accounting for a relatively shorter proportion of time. That the longer tests had higher emissions means that the increase was actually larger than indicated on the figure.

This is reinforced in Figure 35, which shows a comparison of the Mercedes C180 with the VW Passat that was tested at the beginning of this paper, in Step 2. As can be seen, the changes in testing conditions such as test cycle, lower ambient temperature, and engine hot start have significant effects on NO_x emissions of the Mercedes and much lesser impact on the emissions of the VW. For example, the hot start did not increase emissions at all on the Passat at 23°C, and emissions after the hot start were still below the type-approval limit at 0°C. This reinforces our assertion that there is no technical justification for the emissions behavior seen in the Mercedes.

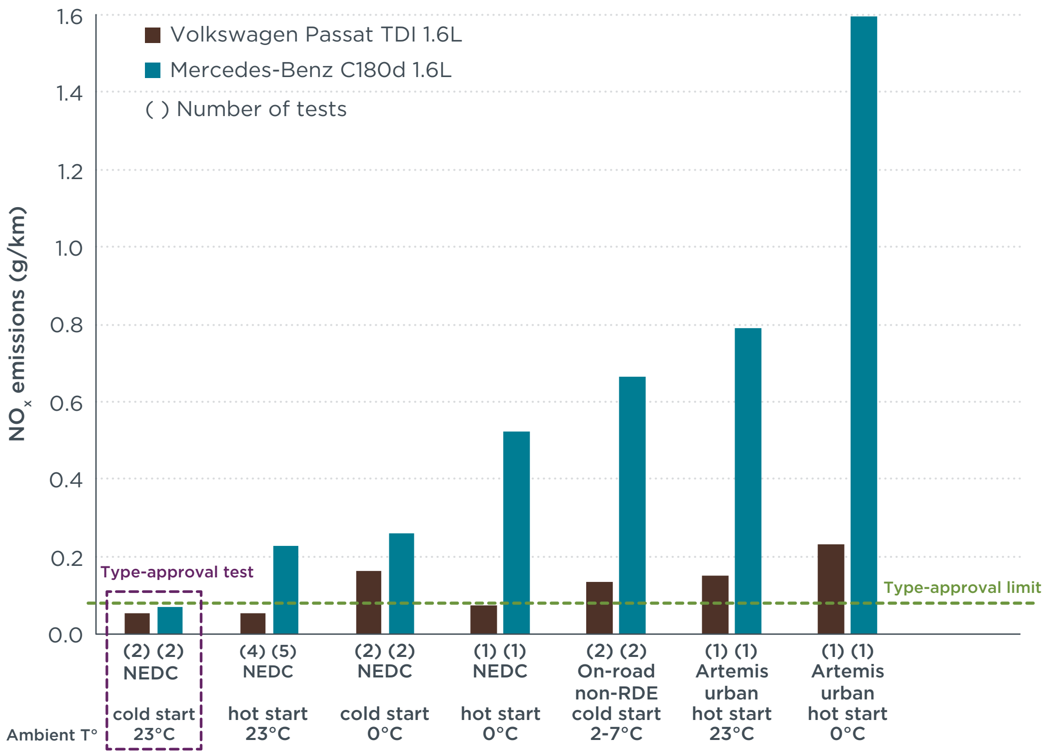

Figure 35: NO_x emissions for the diesel VW Passat and C-Class 180 Mercedes over different test conditions. For repeated test, bars represent average emissions.

STEP 7: DISCUSSION AND ITERATIVE STEPS WITH MANUFACTURERS

After government agencies finish collecting and analyzing test data, the next step would be to approach manufacturers for additional information and responses addressing the list of suspicious calibration changes. Third parties lack the authority to compel manufacturers to respond. The best that third parties can do is to publish their data and hope that either the publicity causes manufacturers to make calibration changes or a regulatory agency picks up the data and approaches the manufacturer, as the EPA and CARB did when presented with the VW diesel test data in 2014.[31] As a third party, we did not approach Mercedes after completion of the test program and analysis described above.

Government agencies should be prepared to conduct additional testing if the explanations from a manufacturer do not make sense or if the manufacturer is not fully cooperating. Additional testing should target resolving disputes or demonstrating that a manufacturer is not fully cooperating. For this process to be effective, it is necessary that the burden be placed on manufacturers to prove that their calibrations and resulting emissions are justified. If no resolution can be reached, it might be necessary to go through legal channels. Thus, it is also important for regulators to have strong legal authority to enforce the defeat-device provisions.

31 Starting Jan. 1, 2019, the RDE fourth legislative package introduces the possibility for third parties to commission independent testing from accredited laboratories (European Commission, 2018). These tests aim to check for in-service conformity emissions, not for defeat devices. Admissible results that can trigger an investigation must remain within the scope of boundaries compliant with the regulation. For evidence built on non-compliant tests, it will still be up to regulatory agencies to decide on taking actions.

CONCLUSIONS AND RECOMMENDATIONS

Nitrogen oxide in vehicle exhaust causes significant harm to public health, particularly in urban areas. In large part, the extent of this public health problem is attributable to "excess" emissions—pollution levels above (often far above) the limits established by regulation, and limits which every new vehicle sold in major global markets is certified as meeting. In Europe alone, about 6,800 deaths due to excess NO_x from cars and vans could be avoided every year if NO_x emissions just from diesel vehicles on the road in the real world fell within the limits defined in the European Union's vehicle emissions regulation (Anenberg et al., 2017).

Defeat-device detection and enforcement is a critical component of ensuring low real-world vehicle emissions. While the United States has a 40-year history of enforcing defeat-device requirements and refining guidance and detection techniques, in Europe diesel NO_x emissions are very high and in most cases government agencies appear unable or unwilling to do much about it. Instead, efforts to control defeat devices in Europe have led to the adoption of RDE provisions.

RDE will certainly help to limit the effectiveness of defeat devices. However, as demonstrated in part by testing of the Mercedes C180 and C200, RDE will continue to allow some defeat devices. For example:

» RDE boundary conditions are fixed, allowing calibration changes beyond the boundary conditions.

» The RDE test sequence is prescriptive, allowing calibration changes for instance if the order or the length of urban, rural, and motorway driving is not followed.

» The impact of cold-start emissions is low due to the long duration of an RDE test. The minimum distance requirements of the test make it mostly a hot engine test, allowing increased emissions after the engine has warmed up. Typical real-world trips are much shorter, therefore with a higher contribution of emissions from cold start.

» The conformity factor is too high, allowing calibration changes after the engine has warmed up that would maintain on-road emissions below the RDE limit but above the laboratory limit.

» Calibrations could be changed based upon detection of PEMS installation, elapsed time since ignition off, or known RDE test routes using GPS.

Stronger enforcement and better-defined provisions are key to offset incentives for manufacturers to use defeat devices. Since Dieselgate, the European Commission has proposed a series of legislative changes to improve defeat-device enforcement:

» A defeat-device guideline for type-approval authorities applicable for NO_x emissions (European Commission, 2017c).

» The need to disclose in the extended documentation package and get approval of any auxiliary emissions strategy (AES) by the type-approval authority, similar to what is done in the United States (European Commission, 2017b). However, it should be noted that U.S. authorities do not issue approvals for an AES during the type-approval process but reserve the right to investigate in-use vehicles and issue recalls if an AES is later found to be an illegal defeat device. This reflects the reality that it is extremely difficult to assess whether an AES is appropriate without extensive testing and instrumentation to find calibration triggers, similar to the testing outlined in this report. Such testing is not possible during the type-approval process. Putting the burden on type-approval authorities to issue approvals during type approval makes it impossible to do a thorough investigation and make an informed decision. The burden of proof needs to be placed on manufacturers, not type-approval authorities (Gabriel & Gabriel, 2016).

» An AES can be used for engine protection only if there is a risk of sudden and irreparable engine damage.

» The notion of "available technology or design" is used to prove that there were no alternatives to the use of an AES (European Commission, 2018).

» A new-type approval framework to improve market surveillance at the member state and EU levels from September 1, 2020 onward. The new regulation allows the European Commission to carry out its own verification testing and impose fines of up to €30,000 per noncompliant vehicle. New rules also require EU member states to conduct a minimum number of vehicle in-use compliance tests per year and grant type-approval authorities and technical services access to vehicle software (Mock, 2018).

Issuing improved guidance is necessary for enforcing defeat-device provisions, but rigorous enforcement testing is still needed to determine whether manufacturers are complying with the guidance. This report provides a seven-step procedure and testing flow charts for agencies and third parties on how to find and identify improper calibration strategies through vehicle testing. Recommendations and procedures described in this report are applicable to other regions around the world.

Following this procedure will provide a sound basis for agencies to begin discussions with manufacturers, or for third parties to prod manufacturers to make corrections, or for regulators to begin enforcement actions:

Step 1: Select a vehicle for testing, based upon pre-screening from other testing and remote sensing

Step 2: Confirm proper vehicle operation on the type-approval test and real-world emissions discrepancies using inexpensive screening sensors

Step 3: Prepare the vehicle and instrumentation for robust emissions testing and investigation of calibration triggers

Step 4: Road test, while changing variables one at a time to identify step changes in emissions

Step 5: Laboratory test, to help identify defeat device triggers for step-changes in emissions

Step 6: Summarize data analyses

Step 7: Discussion and iterative steps with manufacturers (official agencies only)

Based upon the selection criteria in Step 1 and the initial emissions screening in Step 2, the procedures and flow charts in Steps 3 through 5 were applied to two Mercedes C-Class diesels, a C180 and a C200. Both vehicles exhibited inconsistent emissions control and potential defeat-device triggers in their calibration strategies. Using U.S. criteria for enforcing defeat-device provisions, the likely defeat devices identified by the testing were changes in EGR and SCR behavior based upon ambient temperature, EGR changes based on some measure of the engine temperature, and reductions in SCR efficiency possibly based on some sort of timer or measure of urea consumption. There were also possible defeat devices linked to the length of the test and preconditioning before the test. Finally, we found calibrations that limited maximum EGR flow rate to engine conditions found on the NEDC, possibly due to system design limitations. The impacts of these defeat-device triggers seem to be additive, such that combining several of these defeat devices and design limitations leads to NO_x emissions of as much as 20 times the type-approval limit. Real-world emissions under routine urban driving conditions and ambient temperatures are particularly alarming. All of these would be excellent starting points for discussions with Mercedes.

Since the completion of the tests detailed in this report, Germany's federal motor vehicle regulator, the Kraftfahrt-Bundesamt (KBA), has investigated a Mercedes model, the Vito van, equipped with a similar version of the 1.6L engine used in the C180 and C200. KBA found the presence of five deemed illegal defeat devices, but the details of the defeat devices have not yet been made public (Reuters, 2018). In June 2018, it appeared the result of KBA's finding was limited to a mandatory engine software recall of 774,000 Vito vans, GLC sport-utility vehicles, and C-Class sedans in Europe. However, three months later, in September 2018, Daimler released a more extensive list of recalled models (Daimler, 2018). The company has denied any wrongdoing (Behrmann, Jennen, & Rauwald, 2018). The C200 model tested in this project had not received an order of recall for any emissions-related improvement before we returned it in late March 2019.

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APPENDIX

A. VEHICLES CHARACTERISTICS

Table 17: Characteristics of the tested diesel C-Class 180 and 200.

Vehicle characteristics	Vehicle A	Vehicle B
Brand	Mercedes-Benz	Mercedes-Benz
Model	C 180d Bluetec	C 200d Bluetec
Engine displacement (cc)	1,598	1,598
Power version (kW)	85	100
Certification standard	Euro 6b	Euro 6b
Transmission	Automatic 7 Gear	Automatic 7 Gear
Aftertreatment system	DOC+DPF+SCR	DOC+DPF+SCR
Model year	June 2015	March 2015
CO_2 type-approval (g/km)	114	112
NO_x type-approval limit (g/km)	0.080	0.080
NO_x type-approval (g/km)	0.053	0.053
ECU	Bosch	Bosch
Mileage at beginning of testing	15,000 km	23,600 km
Source	Renting company in Finland	Local dealer in UK

B. CO_2 ESTIMATION FROM THE O_2 CONCENTRATION MEASURED BY A NO_X/O_2 SENSOR.

NO_x sensors used in series vehicles can measure simultaneously the NO_x and the O_2 concentration in the exhaust. Our testing used the UniNOx sensor from Continental (Figure 36).

Figure 36: Continental UniNOx sensor measure NO_x and O_2 concentration

The relationship between the O_2 and CO_2 content in the exhaust of diesel vehicles is linear (Vermeulen, Ligterink, Vonk, & Baarbé, 2012). It depends only on the hydrogen to carbon content in the fuel, which varies very little in the EU market. Figure 37 shows the correlation for diesel fuel.

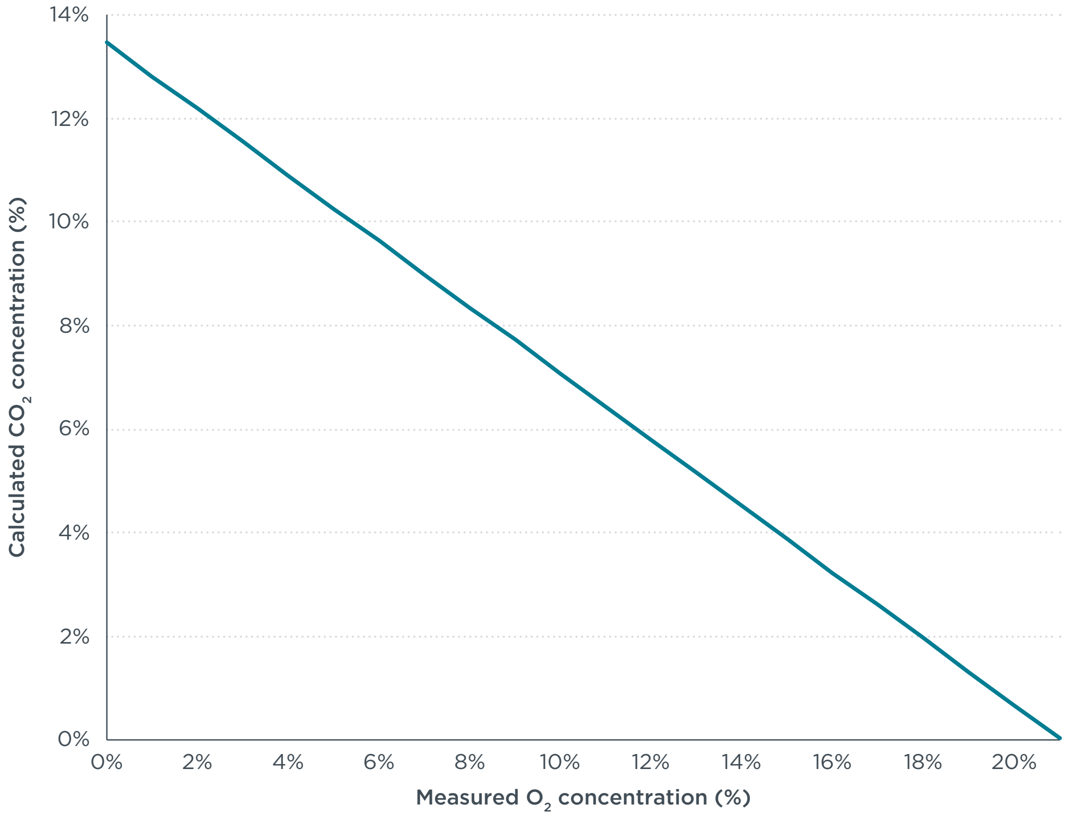

Figure 37: Correlation between exhaust O_2 and CO_2 for diesel fuel.

We used the UniNOx sensor to estimate the CO_2 concentration in the exhaust, in addition to measure NO_x concentration.

C. ESTIMATION OF EGR RATE USING ENGINE AIR FLOW RATE AND TEMPERATURE PARAMETERS

Figure 38 shows vehicle speed and engine-out NO_x emissions for two very similar chassis-dynamometer tests with the same vehicle, the C200. The first was a cold-start NEDC test that followed a pre-conditioning procedure (3xEUDC). The second one was the same test, with no specific pre-conditioning cycle. Even though the vehicle speed traces were almost identical, engine-out NO_x emissions were quite different from about second 1,050 to 1,130.

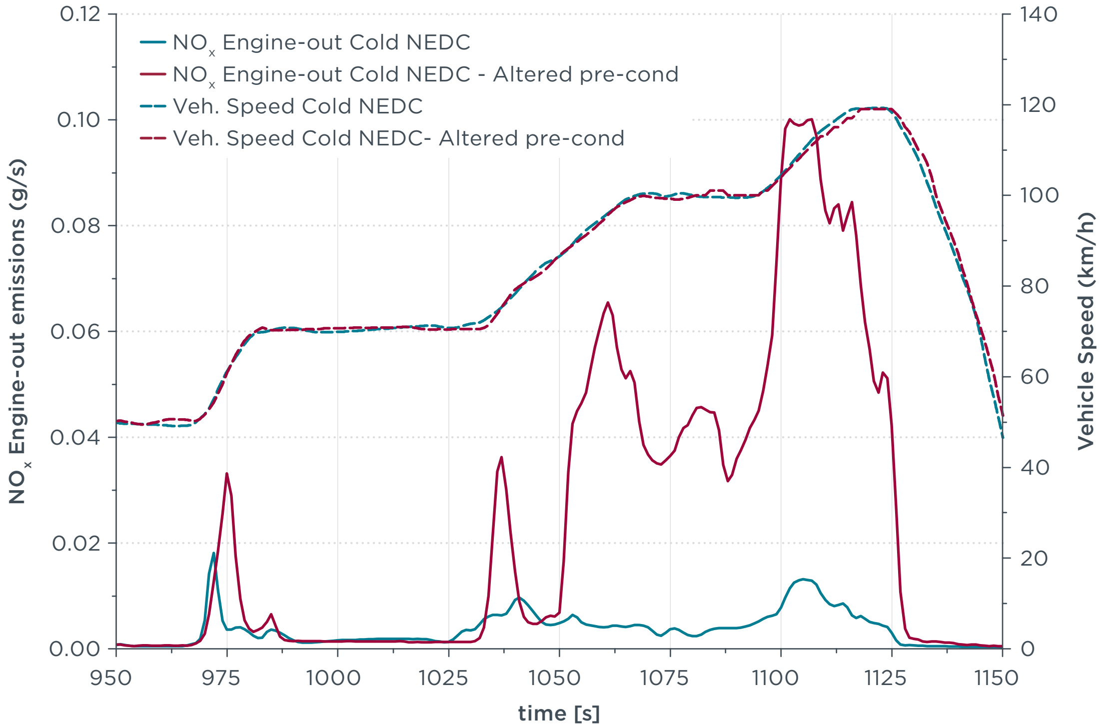

Figure 38: Vehicle speed and NO_x engine-out on the extra-urban section (EUDC) of two NEDC with and without a pre-conditioning test.

Figure 39 shows that the elevated NO_x emissions correspond with higher air mass flow because of exhaust gas recirculation being shut off and lower EGR-out temperatures because of lower EGR flow rate. These signals are reasonably accurate surrogates for EGR rate, especially when comparing EGR strategy between two similar cycles.

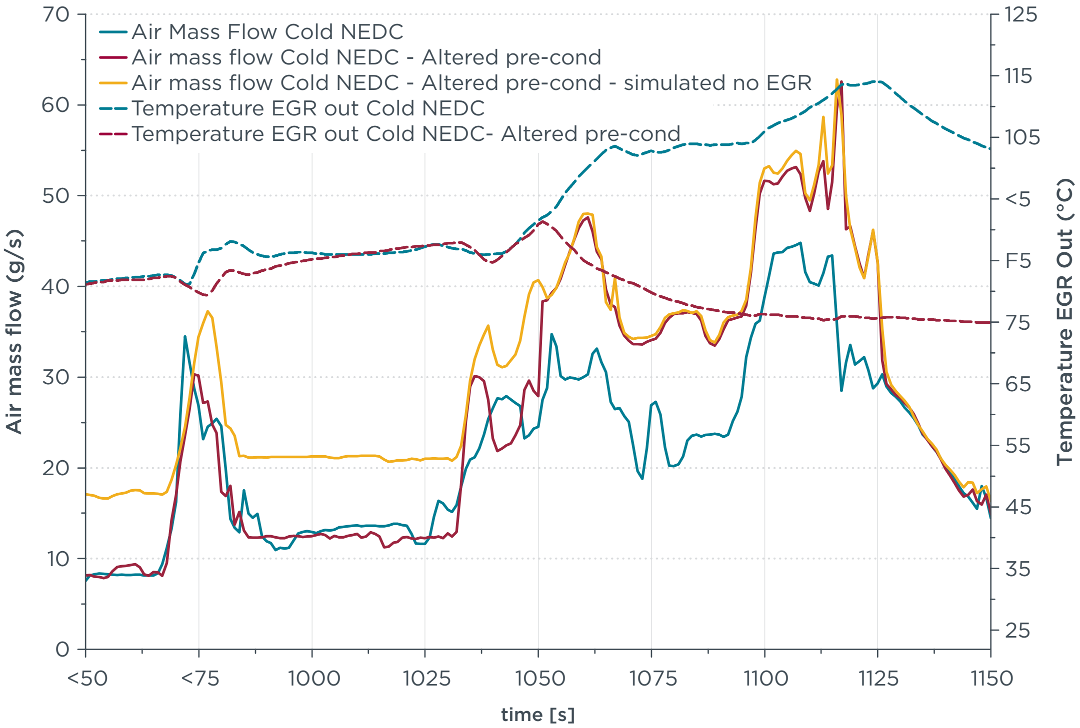

Figure 39: Air mass flow measured and simulated without EGR, and temperature EGR-out comparison on the extra-urban section (EUDC) of two NEDC with and without a pre-conditioning test.

In addition, we can also estimate the theoretical air mass flow, the yellow curve, that the engine would aspirate with a fully closed EGR valve and a fully open air throttle. The estimation depends mainly on the engine speed signal, the measured air boost pressure and temperature, and an estimate of the volumetric efficiency, which is assumed constant during comparable tests. The difference between the measurement and the estimation without EGR gives an estimate of the EGR rate. Figure 40 confirms that highest engine-out NO_x emissions coincide with an EGR rate estimate near zero.

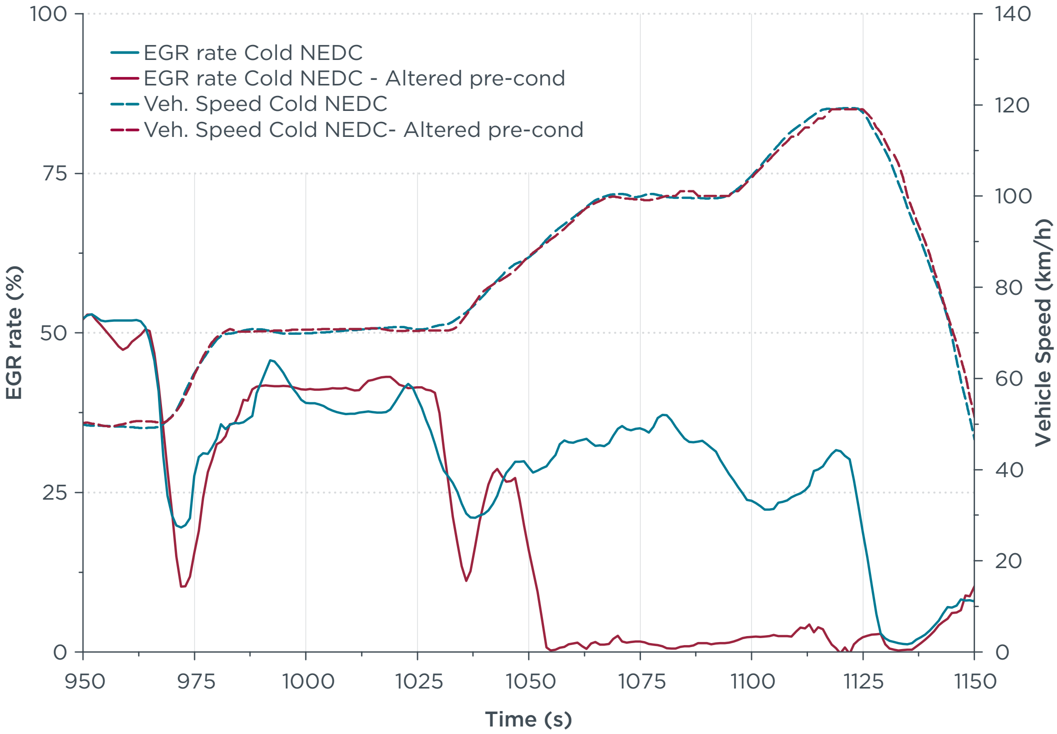

Figure 40: Comparison of EGR rate estimation of the extra-urban section (EUDC) of two NEDC with and without a pre-conditioning test.

Finally, we used expert judgments from the testing company and cross-correlated CO_2 signals to rule out the possibility that a DPF regeneration occurred during the test that could have explained the sudden change of EGR strategy.

D. NO_x CONCENTRATION TO MASS EMISSION ESTIMATION WITHOUT MEASUREMENT OF THE AIR MASS FLOW:

The general formula to calculate exhaust mass emissions such as NO_x over a period of time is the following:

$$\textit{Total emitted mass of } NO_x = \int NO_x \textit{ mass flow rate } (t) \,.\, dt$$

The combined NO_x and O_2 sensor allows calculating the NO_x to CO_2 ratio at any moment (as discussed in Appendix B).

Whatever the exhaust mass flow, the following relation stands where M is the molar mass:

$$\frac{NO_x \textit{ concentration } (t)}{CO_2 \textit{ concentration } (t)} \times \frac{MNO_x}{MCO_2} = \frac{NO_x \textit{ mass flow rate } (t)}{CO_2 \textit{ mass flow rate } (t)}$$

We can write the first formula:

$$\textit{Total emitted mass of } NO_x = \frac{MNO_x}{MCO_2} \times \int \left(\frac{NO_x \textit{ concentration } (t)}{CO_2 \textit{ concentration } (t)} \times CO_2 \textit{ mass flow rate } (t) \right) .dt$$

If the exhaust mass flow rate is not measured, the total NO_x mass emissions over a trip may still be estimated thanks to the total CO_2 mass emission.

Making the simplification that each vehicle trip-overall NO_x /CO_2 emissions can be estimated by the ratio of mean NO_x concentration to the mean of CO_2 concentration, we get:

$$\textit{Total emitted mass of } NO_x \approx \frac{MNO_x}{MCO_2} \times \frac{\textit{mean } NO_x \textit{ concentration}}{\textit{mean } CO_2 \textit{ concentration}} \times \int CO_2 \textit{ mass flow rate } (t) .dt$$

$$\textit{Total emitted mass of } NO_x \approx \frac{MNO_x}{MCO_2} \times \frac{\textit{mean } NO_x \textit{ concentration}}{\textit{mean } CO_2 \textit{ concentration}} \times \textit{Total emitted mass of } CO_2$$

We chose to use the ratio of the mean of NO_x and CO_2, and not the mean of the instantaneous NO_x to CO_2 ratio. The first reason is to avoid the need of synchronizing both signals. Second, during fuel cut-off phases, the CO_2 concentration is measured close to zero. The instantaneous NO_x to CO_2 ratio is therefore very high during such deceleration but does not contribute significantly to total mass emissions over the trip.

Total mass of CO_2 in the equation is a parameter that can be easily approximated, because it is directly linked to fuel consumption. By reporting the fuel consumption estimate, such as is often available on the dashboard, or by measured refueling, we can estimate total CO_2 emissions for a given trip.

For the example of 1 kg of diesel fuel burned, 3.16 kg of CO_2 are emitted.

$$\textit{Total emitted mass of } NO_x \approx \frac{MNO_x}{MCO_2} \times \frac{\textit{mean } NO_x \textit{ concentration}}{\textit{mean } CO_2 \textit{ concentration}} \times 3.16 \times \textit{Total mass of diesel fuel consumption}$$

On a kilometer bases, the equation gives:

$$\textit{Total emitted mass of } NO_x / km \approx \frac{MNO_x}{MCO_2} \times \frac{\textit{mean } NO_x \textit{ concentration}}{\textit{mean } CO_2 \textit{ concentration}} \times 3.16 \times \textit{Total mass of fuel consumption} / km$$

Figure 41 presents the correlation between a large database of 126 PEMS testing results and NO_x calculated using the concentration measurements and fuel consumption estimates. It includes trips of various durations and conditions, such as not necessarily RDE compliant, measured on diesel passenger cars from the European Union and the United States (Franco, Posada Sánchez, German, & Mock, 2014).

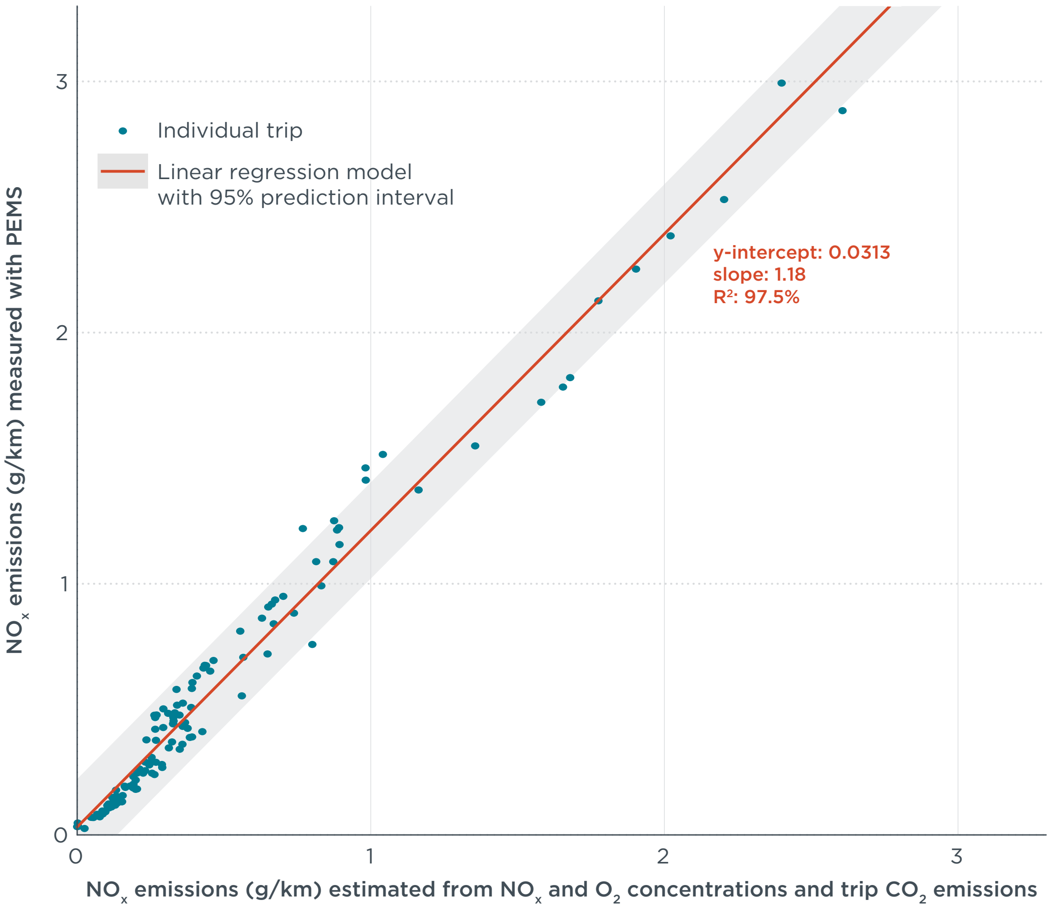

Figure 41: NO_x distance-specific mass emissions compared with estimates using NO_x concentration, CO_2 concentration, and trip CO_2 distance-specific mass emissions

Figure 42 models the trend based on the lowest-emitting trips of as much as 0.3 g/km and calculates a 90% prediction interval. If NO_x emission estimation with our method is above 0.197 g/km, there is a 95% probability that the emissions are not meeting the current Euro6d-TEMP RDE conformity factor of 2.1 limiting diesel on-road emissions to 0.168 g/km.

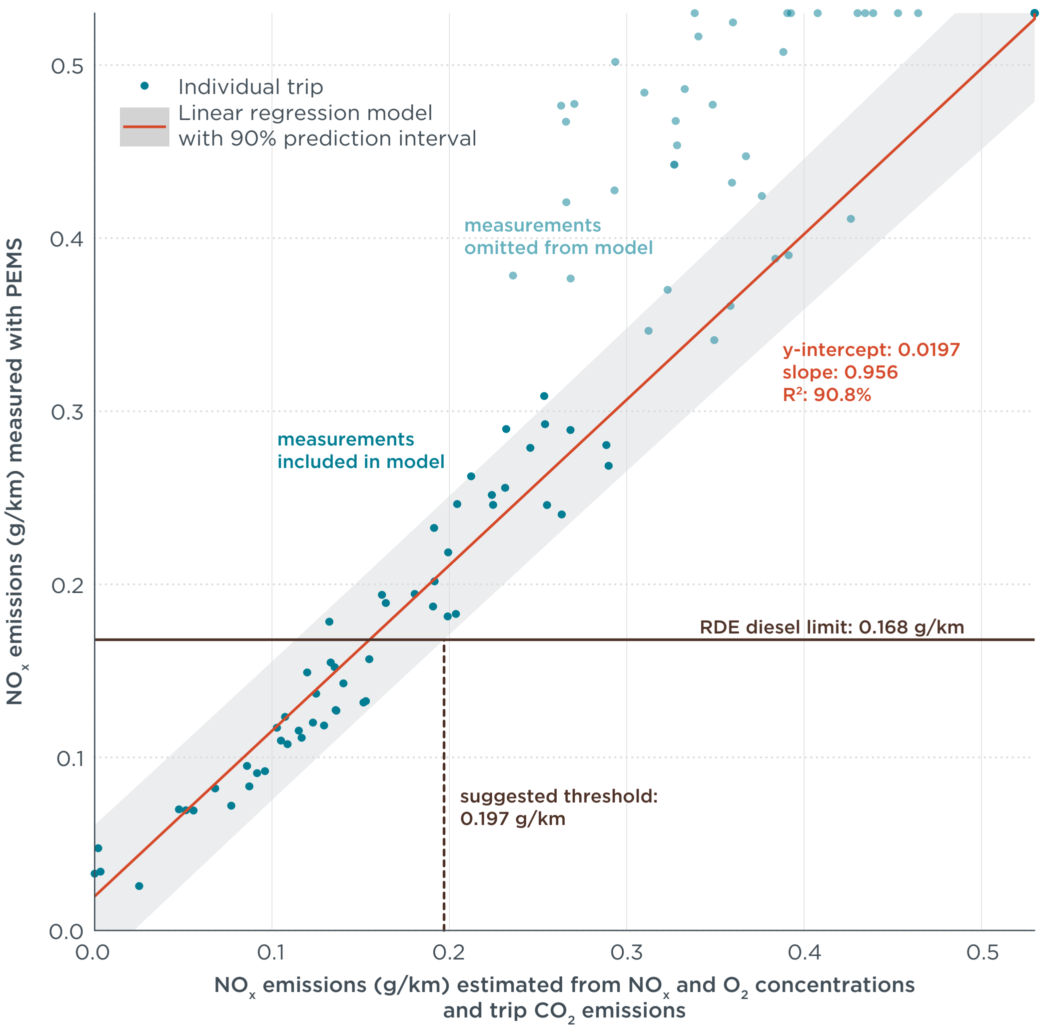

Figure 42: NO_x distance-specific mass emissions compared with an estimation using NO_x concentration, CO_2 concentration, and trip CO_2 distance-specific mass emissions. The 90% prediction interval is calculated based on trips with NO_x below 0.3 g/km and compared with phase 1 of the RDE Not-to-Exceed limit.

E. ADDITIONAL TESTING DATA

Table 18: Detailed results of RDE-compliant test repeated four times on the same route on the Mercedes C200 (expansion of Table 3)

	Run 1				Run 2				Run 3				Run 4			
	Total	urban	rural	motorway	Total	urban	rural	motorway	Total	urban	rural	motorway	Total	urban	rural	motorway
Engine-out NO_x (mg/km) from sensor	813	605	1,301	431	690	533	1,044	406	857	557	1290	471	1,200	1,314	1,511	832
Tailpipe NO_x (mg/km) from sensor	608	435	1,047	260	196	486	195	73	201	146	294	110	553	1,257	593	146
Tailpipe NO_x (mg/km) from PEMS	583	421	1,005	265	230	466	225	87	210	182	293	119	495	1,035	591	65
Tailpipe CO_2 (g/km) from sensor	127	155	126	113	129	148	135	114	134	172	136	110	137	165	139	120
Tailpipe CO_2 (g/km) from PEMS	131	163	127	114	131	147	136	115	135	167	135	111	139	162	141	122
Average SCR NO_x conversion (%)	25	28	20	40	72	9	81	82	77	74	77	77	54	4	61	82
Estimated urea solution consumption (L/1,000 km)	0.39	0.32	0.48	0.32	0.93	0.09	1.60	0.63	1.24	0.78	1.88	0.68	1.22	0.11	1.74	1.3
Estimated required urea solution to meet the Euro 6 limit (L/1,000 km)	1.38	0.99	2.31	0.66	1.15	0.86	1.82	0.62	1.47	0.9	2.29	0.74	2.12	2.33	2.7	1.42
Estimated average EGR rate (%)	14	21	2	20	17	23	9	18	13	22	5	11	5	6	4	1
Ratio to Euro 6 limit (NO_x conformity factor)	7.28	5.27	12.56	3.31	2.87	5.82	2.81	1.09	2.62	2.28	3.66	1.49	6.19	12.94	7.38	0.82
Average ambient temp (°C)	12	11.3	12.3	13.3	14.6	14.5	14.14	15.39	12.7	12.6	12.6	13.3	9.4	8.5	9.6	10.8
Min/Max ambient temp (°C)	10.7/14.3	10.7/12.4	11.2/14.3	12.2/14.2	13.2/16.7	13.5/16.7	13.2/16.0	13.9/16.4	10.6/14.7	10.6/14.5	11.1/14.5	11.9/14.7	7.1/12.6	7.1/12.6	8.5/12.1	10.1/11.9
Average vehicle speed (km/h)	55.6	29	63.3	100.9	56.7	28.6	68.4	101.8	56.6	28.9	69.6	101.7	52.3	28.4	54.6	100.1
Average positive VSP (kW/t)	7.09	3.53	7.1	12	7.26	3.31	7.71	12.38	7.74	3.92	8.49	12.47	7.1	3.58	6.66	12.79
Average SCR inlet temp (°C)	222	185	245	266	218	170	258	266	231	192	264	267	247	212	263	292
Average coolant temp (°C)	84.8	77.8	90.3	91.3	88	85	92	92	84.7	76.8	91.6	91.6	84.9	76.4	91.6	91.4
Coolant temp at test start (°C)	25	25	88	89	56	56	89	90	26	26	85.3	89.4	27	27	89	89
Average intake temperature (°C)	20.6	19.7	20.9	22	24	25	23	24	21.7	19.5	23.2	24.6	19.3	17.4	21	20.3
Average intake pressure (bar)	1.28	1.14	1.33	1.49	1.29	1.14	1.38	1.50	1.3	1.16	1.4	1.49	1.27	1.16	1.3	1.47
Average engine load (%)	33	27	35	43	33	23	40	43	34	28	39	41	34	26	36	47
Average engine RPM	1,415	1,261	1,415	1,758	1,416	1,240	1,440	1,768	1,409	1,242	1,450	1,749	1,366	1,242	1,313	1,730
Average air mass flow (kg/h)	73.3	53.9	85.6	96.4	71	50.2	83.0	99.0	75.31	54.97	89.33	99.97	78.6	65.8	78.8	106.2
Average estimated fuel mass flow (kg/h)	3.3	3	3.3	3.1	3.4	3	3.8	3.9	2.4	1.5	3	3.3	2	1.3	2.1	3
Average exhaust flow rate (kg/h)	76.6	56.9	89	99.5	74.4	53.2	86.8	102.9	77.7	56.5	92.3	103.3	80.6	67.1	80.9	109.3
Average EGR out temp (°C)	-	-	-	-	-	-	-	-	82.3	66.4	89.9	107.6	62.2	52	65.8	77.6
Duration of test (sec)	6,420	2,932	2,127	1,361	6,298	2,976	1,974	1,348	6,398	2,934	2,205	1,259	6,999	2,992	2,461	1,545
Distance (km)	99.3	23.7	37.4	38.1	99.3	23.6	37.5	38.1	99.3	23.6	42.7	33.0	99.3	23.6	37.3	38.3

Table 19: Detailed results of the C200 tested NEDC on-track.

	On-track NEDC 1	On-track NEDC 2
Engine-out NO_x (mg/km), from sensor	798	781
Tailpipe NO_x (mg/km), from sensor	274	257
Tailpipe NO_x (mg/km), from PEMS	240	242
Tailpipe CO_2 (g/km), from sensor	157	151
Tailpipe CO_2 (g/km), from PEMS	156	152
Average SCR NO_x conversion (%)	66	67
Estimated urea solution consumption (L/1,000 km)	0.99	0.99
Estimated required urea solution to meet the Euro 6 limit (L/1,000 km	1.32	1.32
Ratio to Euro 6 limit (NO_x conformity factor)	3.43	3.21
Average ambient temp (°C)	15.6	15.6
Min/Max ambient temperature (°C)	15.2/16.1	14.6/16.2
Average vehicle speed (kph)	33.5	33.5
Average positive VSP (kW/t)	5.24	5.25
Average SCR inlet temp (°C)	213	214
Average coolant temp (°C)	90.6	90.9
Coolant temperature at test start (°C)	90.0	90.0
Average intake temperature (°C)	28.4	31.7
Average intake pressure (bar)	1.19	1.19
Average engine load (%)	28.5	28.0
Average engine RPM	1,084	1,061.5
Average exhaust flow rate (kg/h)	51.3	50.9
Average air mass flow if no EGR (kg/h)	61.8	59.9
Average estimated EGR rate (%)	21	19
Average EGR out temperature (°C)	95.2	95.8
Duration of test (sec)	1,180	1,180
Distance (km)	11.0	11.0

Table 20: Detailed results of the urban part of the RDE test performed on a track, with the same lap repeated 14 times. Cells left blank represent data when the NO_x sensors were not yet active.

LAP	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Engine-out NO_x (mg/km) from sensor	-	378	401	710	1,324	1,301	1,173	1,233	1,156	1,314	1,349	1,403	1,333	1,529
Tailpipe NO_x (mg/km) from sensor	-	115	89	145	267	250	267	284	289	417	501	641	613	649
Tailpipe NO_x (mg/km) from PEMS	314	115	113	194	340	322	334	415[21]	346	448	536	661	656	683
Tailpipe CO_2 (g/km) from PEMS	324	267	234	235	226	223	217	260[21]	220	223	222	221	209	208
Average SCR NO_x conversion (%)	-	70	78	80	80	81	77	77	75	68	63	54	54	58
Estimated urea solution consumption (L/1,000 km)	-	0.50	0.59	1.07	2.00	1.99	1.71	1.79	1.64	1.70	1.60	1.44	1.36	1.66
Estimated required to meet the Euro 6 limit (L/1,000 km	-	0.56	0.61	1.19	2.35	2.31	2.07	2.18	2.03	2.33	2.40	2.50	2.37	2.74
Ratio to Euro 6 limit (NO_x conformity factor)	3.92	1.43	1.42	2.42	4.26	4.03	4.18	5.19	4.33	5.60	6.70	8.26	8.20	8.54
Average ambient temp (°C)	13.7	13.5	13.3	13.3	13.2	13.1	13.1	13.1	13.1	13.1	13.1	13.0	13.0	12.8
Min/Max ambient temp (°C)	13.3/14.1	13.2/13.7	13.1/13.6	13.0/13.5	12.9/13.4	12.9/13.3	12.8/13.3	12.8/13.3	12.8/13.3	12.9/13.4	12.8/13.3	12.8/13.2	12.7/13.1	12.7/13.0
Average vehicle speed (kph)	15.1	15.5	15.7	16.5	16.8	17.0	17.3	16.9	17.1	16.9	17.1	17.8	16.9	15.9
Average SCR inlet temp (°C)	151	202	205	212	212	210	209	212	210	209	212	212	211	210
Average coolant temp (°C)	63.1	78.4	86.9	89.0	89.9	90.0	90.1	90.4	90.1	89.8	89.6	89.6	89.9	90.1
Coolant temp at test start (°C)	55.0	70.0	83.0	88.0	89.0	90.0	90.0	90.0	89.0	89.0	88.0	89.0	89.0	89.0
Average positive VSP (kW/t)	1.97	2.20	1.91	2.34	2.69	2.68	2.55	2.48	2.49	2.44	2.66	2.86	2.31	2.37
Average intake temperature (°C)	24	27	23	23	23	25	29	31	32	33	34	34	34	34
Average intake pressure (bar)	1.14	1.15	1.13	1.15	1.14	1.15	1.15	1.14	1.14	1.15	1.15	1.16	1.13	1.13
Average engine load (%)	42.2	32.6	29.6	27.2	25.3	24.7	25.0	24.0	24.6	25.0	24.7	25.1	23.4	23.8
Average engine RPM	1,176	1,141	1,127	1,195	1,147	1,168	1,169	1,150	1,180	1,191	1,182	1,189	1,150	1,112
Average air mass flow (kg/h)	39.6	38.8	37.4	45.2	49.5	49.0	49.6	41.1	49.2	50.0	51.2	51.9	47.7	48.1
Average estimated fuel mass flow (kg/h)	1.5	1.4	1.2	1.3	1.3	1.3	1.3	1.2	1.2	1.3	1.3	1.3	1.2	1.2
Average exhaust flow rate (kg/h)	41.2	40.2	38.6	46.5	50.9	50.3	50.9	42.2	50.5	51.3	52.5	53.2	48.9	49.2
Average air mass flow if no EGR (kg/h)	61.7	60.5	59.7	64.5	62.1	63.1	62.0	60.2	61.4	62.2	61.8	62.8	59.1	57.2
Average estimated EGR rate (%)	34%	36%	37%	30%	19%	21%	19%	20%	19%	19%	18%	17%	19%	16%
Average EGR out temperature (°C)	61	88	97	100	97	98	98	99	99	99	99	99	98	97
Duration of test (sec)	302	304	299	285	282	279	273	280	276	279	277	265	281	296
Distance (km)	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3

Table 21: Master table of laboratory testing and NO_x emissions.

Test #	Vehicle	Test Description	Tailpipe NO_x CVS (g/km)
B0	C200	Type-approval NEDC cold start test with "cook book" road load at 23°C ambient air	0.064
B1	C200	Type-approval NEDC cold start test with real road load at 23°C ambient air	0.068
B1 urban only	C200	Urban portion of type-approval B1 test	0.133
B2	C200	Same as B1 test with Rear gear engaged before start Rear hatch closed Steering wheel movement before start Seat belt of the driver buckled OBD disconnected No modal measurement	0.077
B3	C200	Same as B1 test with OBD disconnected	0.062
B4	C200	Same as B1 test with AC on	0.122
B5	C200	Same as B1 test with altered preconditioning	0.408
B6	C200	Same as B1 test performed at 14°C ambient air	0.052
B7	C200	Same as B1 with engine started warm (coolant >70°C), engine off 30-45 minutes after a B1 test	0.038
B8	C200	Same as B1 with engine started warm (coolant >70°C), engine idling 30-45 minutes after a B1 test	0.202
B9	C200	Artemis urban cold start at 23°C ambient air	0.399
A1	C180	Type-approval NEDC cold-start test at 23°C ambient air	0.069
A2	C180	Same as A1 test performed at 12°C ambient air	0.389
A3	C180	Same as A1 test performed at 0°C ambient air	0.262
A4	C180	Same as A1 with engine started warm (coolant >70°C), engine off 10-20 minutes after a A1 test	0.214
A5	C180	Artemis urban cold start at 23°C ambient air	0.469
A6	C180	Artemis urban hot start at 23°C ambient air	0.790
A7	C180	Artemis urban hot start performed at 12°C ambient air	1.243
A8	C180	Artemis urban hot start performed at 0°C ambient air	1.596

Table 22: Detailed results of laboratory tests aiming to detect switch type of defeat device. Cells left blank represent data we did not obtain for that test.

TEST	A1	B1	B2	B3
Engine-out NO_x modal (mg/km)	-	161	-	158
Tailpipe NO_x modal (mg/km)	-	69	-	62
Tailpipe NO_x CVS (mg/km)	69	68	77	62
Tailpipe CO_2 modal (g/km)	-	143	-	143
Tailpipe CO_2 CVS (g/km)	136	140	145	143
Average SCR NO_x conversion (%)	-	57	-	61
Estimated urea solution consumption (L/1,000 km)	-	0.17	-	0.18
Ratio to Euro 6 limit (NO_x conformity factor)	0.86	0.86	0.96	0.77
Average ambient temp (°C)	23	23.8	25	
Average vehicle speed (kph)	32.2	32.1	33.2	33.2
Duration of test (sec)	1,180	1,180	1,180	1,180
Average coolant temperature (°C)	-	58	-	-
Coolant temp at test start (°C)	22	22	-	-
Average intake manifold temp (°C)	-	28.3	-	34.9
Average intake manifold pressure (kPa)	-	1.12	-	-
Average engine load (%)	-	31	-	-
Average engine RPM	-	1,014	-	-
Average EGR out temperature (°C)	-	52.7	-	-
Average estimated EGR rate (%)	-	26	-	-

Table 23: Detailed results of laboratory test results that should have a limited impact on emissions.

TEST	B1	B4	B5
Engine-out NO_x modal (mg/km)	161	374	556
Tailpipe NO_x modal (mg/km)	69	106	376
Tailpipe NO_x CVS (mg/km)	68	122	408
Tailpipe CO_2 modal (g/km)	143	185	143
Tailpipe CO_2 CVS (g/km)	140	183	140
Average SCR NO_x conversion (%)	57	72	32
Estimated urea solution consumption (L/1,000 km)	0.17	0.51	0.34
Ratio to Euro 6 limit (NO_x conformity factor)	0.86	1.33	4.70
Average ambient temp (°C)	23.8	22.8	24.1
Average vehicle speed (kph)	32.1	32.7	33.2
Duration of test (sec)	1,180	1,180	1,180
Average coolant temp (°C)	58	62	60
Coolant temp at test start (°C)	22	21	22
Average intake manifold temp (°C)	28.3	38.5	27.5
Average intake manifold pressure (kPa)	1.12	1.14	1.11
Average engine load (%)	31	39	31
Average engine RPM	1014	1024	1043
Average EGR out temp (°C)	52.7	57.0	51.0
Estimated EGR rate	26	18	18

Table 24: Detailed results of laboratory tests with lower ambient temperature. Cells left blank represent data we did not obtain for that test.

TEST	B1	B6	A2	A3
Engine-out NO_x modal (mg/km)	161	198	-	-
Tailpipe NO_x modal (mg/km)	69	54	-	-
Tailpipe NO_x CVS (mg/km)	68	52	389	262
Tailpipe CO_2 modal (g/km)	143	161	-	-
Tailpipe CO_2 CVS (g/km)	140	159	139	162
Average SCR NO_x conversion (%)	57	73	-	-
Estimated urea solution consumption (L/1,000 km)	0.17	0.27	-	-
Ratio to Euro 6 limit (NO_x conformity factor)	0.86	0.67	4.86	3.28
Average ambient temp (°C)	23.8	14.6	12.0	0
Average vehicle speed (kph)	32.1	32.5	32.4	32.7
Duration of test (sec)	1,180	1,180	1,180	1,180
Average coolant temp (°C)	58	58	-	-
Coolant temp at test start (°C)	22	17	12	0
Average intake manifold temp (°C)	28.3	23	-	-
Average intake manifold pressure (kPa)	1.12	1.12	-	-
Average engine load (%)	31	33	-	-
Average engine RPM	1,014	1,040	-	-
Average EGR out temp (°C)	52.7	52	-	-
Estimated EGR rate (%)	26	25	-	-

Table 25: Results of laboratory tests with hot start, starting from engine idling, or ignition off with different soaking times. Cells left blank represent data we did not obtain for that test.

TEST	B1	B7	B8	A1	A4
Engine-out NO_x modal (mg/km)	161	536	577	-	-
Tailpipe NO_x modal (mg/km)	69	32	193	-	-
Tailpipe NO_x CVS (mg/km)	68	38	202	69	214
Tailpipe CO_2 modal (g/km)	143	134	129	-	-
Tailpipe CO_2 CVS (g/km)	140	131	127	136	126
Average SCR NO_x conversion (%)	57	94	67	-	-
Estimated urea solution consumption (L/1,000 km)	0.17	0.95	0.73	-	-
Ratio to Euro 6 limit (NO_x conformity factor)	0.86	0.40	2.41	0.86	2.68
Average ambient temp (°C)	23.8	25.0	24.1	23	23.0
Average vehicle speed (kph)	32.1	34.1	33.0	32.2	23.0
Duration of test (sec)	1,180	1,180	1,180	1,180	1,180
Average coolant temp (°C)	58	-	88	-	-
Coolant temp at test start (°C)	22	-	85	22	-
Average intake manifold temp (°C)	28.3	-	38.0	-	-
Average intake manifold pressure (kPa)	1.12	-	1.13	-	-
Average engine load (%)	31	-	25	-	-
Average engine RPM	1,014	1,067	1,036	-	-
Average EGR out temp (°C)	52.7	-	92.8	-	-
Estimated EGR rate (%)	26	-	16	-	-

Table 26: Results of laboratory tests with urban NEDC and urban Artemis cycle. Cells left blank represent data we did not obtain for that test.

TEST	B1 urban only	B9	A5
Engine-out NO_x modal (mg/km)	208	506	-
Tailpipe NO_x modal (mg/km)	133	399	-
Tailpipe NO_x CVS (mg/km)	130	400	469
Tailpipe CO_2 modal (g/km)	177	256	-
Tailpipe CO_2 CVS (g/km)	169	247	251
Average SCR NO_x conversion (%)	36	21	-
Estimated urea solution consumption (L/1,000 km)	0.14	0.20	-
Ratio to Euro 6 limit (NO_x conformity factor)	1.66	4.99	5.86
Average ambient temp (°C)	23	23	23
Average vehicle speed (kph)	17	17	17
Duration of test (sec)	780	1,009	1,009
Average coolant temp (°C)	49	60	-
Coolant temp at test start (°C)	22	23	-
Average intake manifold temp (°C)	27	28	-
Average intake manifold pressure (kPa)	1.04	1.08	-
Average engine load (%)	24	28	-
Average engine RPM	837	952	-
Average EGR out temp (°C)	38	56.0	-
Estimated EGR rate (%)	28	20	-

Table 27: Results of the C180 laboratory tests with urban Artemis cycle from a cold and hot start at 23°C, and from hot start at 12°C and 0°C.

TEST	A5	A6	A7	A8
Tailpipe NO_x CVS (mg/km)	469	790	1,243	1,596
Tailpipe CO_2 CVS (g/km)	251	238	227	241
Ratio to Euro 6 limit (NO_x conformity factor)	5.86	9.88	15.54	19.95
Average ambient temp (°C)	23	23	12	0