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TNO report

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Update: Assessment of risks for elevated emissions of vehicles outside the boundaries of RDE

Identifying relevant driving and vehicle conditions and possible abatement measures

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More specifically, TNO wishes to acknowledge the stakeholders below:

- RDW: The Netherlands Vehicle Authority
- ICCT: International Council on Clean Transportation Europe
- DG JRC: Directorate General Joint Research Centre, Sustainable Transport Unit, Ispra Italy
- TÜV Hessen: Technische Überwachung Hessen
- T&E: Transport & Environment

Management summary

With RDE (Real Driving Emissions) legislation a new chapter in emission testing has started for light-duty vehicles. RDE legislation poses new and more complex engineering targets for manufacturers. The expectation is that RDE will bring major improvements in the emission performance of LD vehicles for a large part of vehicle usage on European roads. However, a number of special, but not necessarily uncommon situations fall outside the boundaries for the test and vehicle conditions specified within the RDE legislation. It is important to ensure that the effectiveness of emission control strategies, or emission control systems, is guaranteed even in conditions that fall outside the scope of the RDE test conditions.

Following the Heavy Duty regulation and also equivalent to the US legislation there is in RDE 2 the requirement introduced that the manufacturer will supply to the Granting Type-Approval Authority (GTAA) information on emission control strategies, i.e., the BES (Base Emission Strategy) and the AES (Auxiliary Emission Strategy). The Base Emission Strategy (BES) should be active inside but also outside the RDE boundaries unless there is an Auxiliary Emission Strategy (AES) approved by the granting type approval authority. This documentation is assessed by the GTAA based on the requirements in RDE 3 and on the guidance notice from the European Commission on the evaluation of Auxiliary Emission Strategies and the presence of Defeat Devices published on the 26 January 2017 (C(2017) 352 final).The GTAA may accept elevated emission in specific circumstances. Parts of this information are confidential and will not be available to third parties. The expected effect of an AES on pollutants and CO_2-emissions needs to be reported by the manufacturer and is part of the evaluation by the GTAA. The magnitude of the increase of emissions is not tested and the occurrences of the AES in normal use, is not assessed. Therefore, rather than focussing on the declaration of an AES, as in RDE legislation, this report mainly focusses on circumstances and causes of elevated emissions, which may be observed in monitoring and independent testing, outside the premises of type approval. Only existing technologies to reduce emissions are considered.

Moreover, a focus on emission reductions under RDE conditions only, means the “normal use” in emission legislation set out in article 5(1) of the Euro 5/6 regulation is interpreted as RDE conditions, which excludes beforehand other common driving conditions: “*The manufacturer shall equip vehicles so that the components likely to affect emissions are designed, constructed and assembled so as to enable the vehicle, in normal use, to comply with this Regulation and its implementing measures.”*

The **Ministry of Infrastructure and Water Management** in the Netherlands has requested TNO to identify potential risks for elevated emissions in situations which might occur across Europe but are not covered by RDE.

The aim of this study is to provide an overview of driving and vehicle conditions with possibly elevated emissions. In addition, the study aims to provide guidance on how to detect and assess such situations and identifies possible technical abatement measures.

Although for specific situations suggestions are given for acceptable levels of increase of the emissions, the intention of this document is not to propose new limits for the RDE legislation or to question RDE boundaries. RDE legislation will cover the majority of European driving conditions, or at least what is considered normal use.

The overview of special situations with possibly elevated emissions, or the presence of an AES, and the proposed guidance for assessment are meant for type approval authorities and other third parties which perform tests. Charting the variations could be the basis for risk-based monitoring and surveillance programs. Insights from these programs can help to secure low emissions in various real-world circumstances.

In this study the focus is solely on passenger cars, both diesel-powered as well as petrol-powered engines. For petrol vehicles the assessment is made for both port fuel injected (PFI) and direct injected (DI) engines. The situations with possibly elevated emissions are related to ‘ambient and road conditions’, ‘trip composition’, ‘driving behaviour’ and ‘vehicle conditions’. Examples of possible situations with potential elevated emissions are:

- Driving or starting in ambient temperatures lower than minus 7 ˚C;
- Driving at altitudes higher than 1300 meter;
- Trip or trip sections, deviating in time, distance and/or sequence of the road types compared to a valid RDE trip;
- Aggressive driving dynamics: Higher ‘v*a positive’ (speed multiplied with acceleration) values than allowed according to the RDE legislation;
- Incidental or prolonged motorway driving at higher speeds than 145 km/h;
- Traffic congestion on the motorway;
- Towing a trailer or caravan.
- Air conditioning operation at ambient temperature higher than 30 ˚C

An inventory is given of possible technical reasons for the potentially elevated emissions in these cases. A technical reason for higher NO_x emissions of diesel-powered vehicles at low temperatures can, for example, be a modified EGR rate to reduce the risk of condensation in the inlet manifold and EGR intercooler. However, in some situations a different emission control strategy may be the result of efforts to optimize the strategy to comply with the RDE legislation rather than having low emissions in all real-world conditions. For petrol-power vehicles low temperatures can be an issue as well. Low temperatures can cause inhomogeneity in the air-fuel mixture due to incomplete evaporation of the fuel in the inlet port or cylinder, depending on the type of engine. Inhomogeneity of the air-fuel mixture can cause elevated PN emissions and it can require a rich air/fuel ratio to ensure sufficient fuel evaporation while the engine is still cold, which the catalyst cannot reduce.

In petrol vehicles rich air/fuel ratio at high loads are often observed. This reduces HC and CO catalyst conversion efficiency to very low levels, and it significantly decreases NOx catalyst conversion efficiency. It creates large amounts of CO emission. Due to the extremely high catalyst conversion efficiencies when gasoline engines run at stoichiometry, enrichment results in roughly an order of magnitude increase in HC emissions. Moreover, it gives two orders of magnitude increase in CO emissions and substantial NOx and PN emissions.

Based on the possible technical reasons for elevated emissions proposals for acceptable levels of increase are given. For example, CO_2 emissions correlate quite well with engine power. When excessive high engine loads occur, elevated emissions, equivalent to the increase in CO_2 emissions could be considered acceptable. The correlation between CO_2 emissions and the relevant emission constituent during the WLTC can be taken as reference for the application of such a factor.

Possible technical options to lower the emissions in these kinds of situations are also identified. A few examples of technical options are:
- Applying an alternative or additional emission control system/strategy such as a NO_x storage catalyst for low exhaust temperatures, gaseous ammonia in the SCR system, a closed coupled SCR/DPF, or water injection;
- Improved temperature management, like improved insulation and rerouting the air flow to the engine;
- (Mild) hybridization to avoid long idling and low load periods which cool down the catalyst.
- Application of a Gasoline Particulate Filter

The identified situations can occur in countless combinations during real-world driving. For example, a family of four or five on summer holiday has a fully packed car, so they may need a roof box to carry all the luggage. On a hot summer day, they may drive for extended periods at high speed across Europe to their holiday destination with the air-conditioning at full blaze and maybe the window partly open to have some fresh air in the hot and packed car. To keep the kids entertained one or more DVD players may be running in the back seat. This kind of non-average, but also not uncommon vehicle use is in many ways outside the RDE test boundaries.

It should be mentioned that in many cases applying emission reduction measures are not an isolated single change to a vehicle. There is a certain trade-off between low emissions and other aspects of engine and vehicle design and performance. Aspects such as fuel economy, engine wear and costs can be in competition with the application of emission reduction. Each manufacturer will likely make its own judgement how to balance the different criteria in the design choices. However, such aspects should not be the sole license to switch off emission control systems when the vehicle is operated in conditions which are not covered by the RDE legislation, because in principle the same BES should be active. Switching to fuel enrichment just outside RDE boundaries would result in very high levels of unnecessary emissions. At minimum, the vehicle should make the best possible use of the applied technologies on the vehicle also in conditions outside the RDE boundaries. If the applied technologies are partly or fully deactivated, clear justification and evidence should be supplied by the vehicle manufacturer. For petrol vehicles such strategies for the emission control system are not identified.

The identified trade-offs for petrol vehicles are mainly related to the kind of applied engine and aftertreatment technologies. Still, there is a risk for elevated emissions outside the specified RDE conditions because certain technologies may be not fully effective in certain circumstances.

Contents

1 Introduction

Background
With RDE (Real Driving Emissions) legislation a new chapter in emission testing has started for light-duty vehicles. This kind of legislation is a good step forward to secure low pollutant exhaust emissions in many real-world circumstances. In 2016, TNO performed a rather extensive assessment of the strengths and weaknesses of this new European RDE test procedure[1].

The expectation is that RDE will bring major improvements for a large part of vehicle usage on the European roads. However, in specific situations, relating to non-average weather conditions, driving locations, traffic situations and vehicle configurations, the real-world vehicle emissions may not benefit fully from RDE legislation. RDE legislation poses new and more complex engineering targets for manufacturers. Boundaries for the test and vehicle conditions are specified within the RDE legislation. Boundary conditions, however, entail the risk that emission control strategies are focused on situations inside the boundaries. This could lead to elevated emissions occurring in situations outside of these boundaries due e.g. to different emission control strategies.

With RDE3 legislation, the Granting Type-Approval Authority (GTAA) will approve the Auxiliary Emission Strategy (AES) declared by the manufacturer with information why an AES is needed to avoid engine damage. The underlying assessment will be based on a technical reasoning. For the stakeholders which are active in market surveillance or in-service conformity testing, access to these approvals would very much help for the evaluation of emission test results.

The extended documentation package is possibly commercially sensitive and may include elements of intellectual properties from a vehicle manufacturer. Hence, this assessment and the outcome is not generally available for other parties. Therefore, this information cannot be reviewed and compared with findings from, for example, monitoring programmes. A summary of the effects on emissions of the AESs present, without revealing commercially sensitive information, would improve the overall transparency. With such a summary, that should be part of publicly available documentation, complex discussions on test results of independent parties can be avoided.

The procedure and interpretation of the AES evaluation may vary between different GTAAs. However expert meetings of TAAEG (Type Approval Authorities Expert Group) and meetings involved the Commission with experts from the Member States (TCMV) may assist in common understanding.

A declaration of BES/AES (Basic Emission Strategy/Auxiliary Emission Strategy) by the manufacturer, is based on the USA legislation, where the EPA as a single authority collects and reviews all declarations. Moreover, the EPA performs their own testing, and it has the freedom to assess the declaration. In Europe, the

[1] Strengths and weaknesses of the new European RDE test procedure, see: http://publications.tno.nl/publication/34622349/F3ewoI/TNO-2016-R11227.pdf

situation is very different. There are many GTAAs following a strict type-approval test protocol. Testing outside RDE has no place yet in the European system. In that respect the BES/AES declaration is still an administrative exercise.

The situation can occur that in monitoring programs, and by independent testing, high emission results have been approved by the GTAA on the basis of a technical assessment based on the documentation of the manufacturer. These high emission can have an impact on the environment due to the frequency of occurrences. For example, the RDE test does not cover longer than thirty minutes motorway driving. If emissions increase after thirty minutes on the motorway, it would be part of normal driving, but it is not of any RDE test. The manufacturer could have argued the engine needed protection against overheating due to high engine load, but may have failed to disclose this overheating occurs already while driving for longer periods on the motorway.

Deviating emission control strategies can potentially cause a significant increase in pollutant emissions. This has been particularly true for NO_x emissions of diesel vehicles. For example, an effective EGR (Exhaust Gas Recirculation) can lower the NO_x emissions up to approximately 60%. An SCR (Selective Catalytic Reduction) system can even reach a NO_x conversion of more than 90%. When these kinds of systems are partly or completely inactive, by malfunction or by deliberate disabling, NO_x emissions can increase more than tenfold compared to the Euro 6 limit of 80 mg/km. This level of emissions have been reported for previous diesel vehicles. But even for modern Euro 6dTemp diesel vehicles, elevated emissions may occur in specific situations like dynamic driving as reported recently by the JRC, see Figure 1.

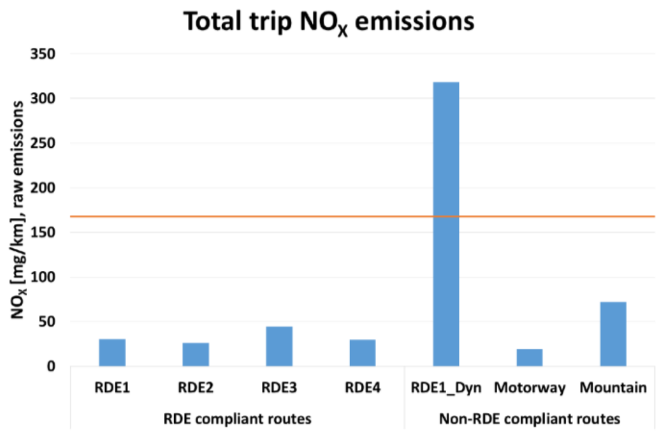

Figure 1: Emissions over different RDE compliant and non-compliant trips as measures by the JRC[2]. The measured vehicle is an Euro 6dTemp equipped with EGR, DOC, SCR and DPF technology.

The low emission levels for petrol vehicles, with a properly functioning three-way catalyst, will result in relatively high emissions for the cases the emission control fails or is circumvented. In current real-world operation, petrol vehicles contribute little to the total emissions, with high NO_x emissions of diesel vehicles. But with

[2] JRC: Scientific evidence on vehicle's emissions: https://ec.europa.eu/docsroom/documents/32164/attachments/3/translations/en/renditions/native

RDE legislation in place, they may constitute remaining issues in improving air-quality.

In many cases emission reduction is not trivial. There often is a certain trade-off between low emissions and other vehicle aspects. Therefore, efforts may be made to optimize the emission control strategy, and/or emission control systems, to comply with the RDE legislation rather than to achieve low emissions in all real-world conditions.

Aim and approach
The Ministry of Infrastructure and Water Management in the Netherlands have requested TNO to identify possible situations, which may occur across Europe but are not covered by the RDE test. If emission control strategies, applied to vehicles in response to the RDE legislation, would be focused on situations inside the RDE boundaries, driving in situations outside the RDE boundaries entails a risk of elevated emissions. Clearly, within a valid RDE trip high emissions events can occur as well. These high emissions can, to a certain extent, be compensated by lower emissions during other parts of the RDE trip. In this study, emissions are defined as ‘elevated’ when a certain situation entails higher emissions than could be expected from a vehicle’s emission behaviour within the boundary conditions of RDE.

Examples of situations outside the RDE boundaries with possibly elevated emissions

The RDE test conditions were never meant to cover all situations that might occur when driving on European roads, but were introduced in order to cover what the legislators considered as normal conditions of use. The general thinking was that each boundary condition with respect to temperature, dynamics, altitude gain, and other aspects would cover 95% of all kilometres driven on European roads. However, as conditions outside the 95% interval for each parameter can occur in countless combinations during real-world driving, eventually much less than 95% of all driving may be within the combined boundaries of RDE.

Here a few examples of use cases are described where such combinations are relevant. The review by TÜV Hessen inspired TNO to describe these use cases. They also clearly illustrate that these situations, although they can be considered outside the scope of "normal driving", are not rare and can constitute a significant part of the annual mileage of various groups of vehicle users.

<u>Family on holiday</u>
A family of 4 or 5 going on a summer holiday has a fully packed car, so they may need a roof box to carry all the luggage. They drive for extended periods at high speed on European highways to their holiday destination. On a hot summer day, the air-conditioning may be at full blaze, the cool box plugged in to the 12-volt system, and maybe a window is partly open to have some fresh air in the hot and packed car. One or two DVD players may be running in the back seat to keep the kids entertained. The combination of additional weight, the air drag of the roof rack and open window, the long periods of high speed driving, and the high use of auxiliary power is outside the RDE boundaries in many ways. The total distance driven under these conditions easily amounts to 10 to 20% of the vehicle's annual mileage. Moreover, during a one hour stop at the motorway restaurant, with the car fully exposed to the sun, the car will become very hot and temperatures may exceed 35 ˚C. Such conditions lie outside the RDE boundary for soak in both the temperature range and soak period.

<u>German business driving</u>
Long distance driving on the German motorway, with speeds above 145 km/h, is quite normal for many drivers, who spend many hours on the road for work. On the autobahn without speed limits this is normal practice. Such driving lies outside RDE, both in velocity and in duration. This means that for the share of German cars with the highest annual mileages, and therefore a substantial contribution to the total distance travelled in Germany, a large part of their driving is not covered at all by RDE.

<u>Trailer or caravan towing</u>
Towing a heavy trailer or caravan may be the reason to buy a high-powered car or van. On the motorway driving with a trailer or caravan occurs at a lower velocity than is prescribed in RDE as motorway velocity. But the engine load can be substantially higher than covered in the RDE. Towing uphill adds further to the load. Hence, the extent to which trailer and caravan towing lies outside the RDE boundaries can be substantial.

<u>Winter period</u>
At -10 ˚C with roads often (potentially) covered with ice or snow, cars drive slowly and carefully to avoid slipping off the road. Prior to driving, the engine is kept running for several minutes to defrost the windows and warm the cabin. Not only the ambient temperature and idling are outside RDE boundaries, but also the snow on the road would not be appropriate for an RDE test. The slow driving will also be outside the RDE boundaries for urban and motorway driving. Still, in many parts of Europe, this situation is a familiar winter scene.

In this study the focus is solely on passenger cars, both diesel-powered as well as petrol-powered engines. For petrol vehicles the assessment is made for both port fuel injected (PFI) and direct injected (DI) engines. This document provides a non-exhaustive overview of situations with possibly elevated emissions. In addition, the study provides guidance on how to detect and how to assess such situations. Although suggestions for acceptable levels of emission increase are given for specific emissions, the intention of this document is not to propose new limits for the RDE legislation or to question RDE boundaries. RDE legislation covers most of European driving conditions. Eventually, type approval authorities (TAA's), or other third parties which perform tests, may use the inventory of emission risks from this document to assess to what extent measures applied to meet RDE requirement lead to acceptable emission levels under all relevant driving conditions.

This document is not a one-time exercise but rather is intended as a living document that can be expanded over time.

As this is a relevant topic for type approval authorities (TAAs), the RDW (Dutch TAA) has contributed to this report by extensive discussions.

Structure of the report
The focus of this report is on situations where RDE boundary conditions may be exceeded. However, elevated emissions are also possible in situations which are related to other parts of the regulated emission checks. Therefore, after this introduction, type approval risks versus risks over the lifetime of a vehicle are identified in chapter 2. Then, in chapter 3 the boundaries of the RDE test and vehicle conditions are described. In chapter four the situations with possibly elevated emissions are identified for diesel-powered vehicles. The identified situations are related to 'ambient and road conditions', 'trip composition', 'driving behaviour' and 'vehicle conditions'. For each identified situation, TNO has considered the possible reasoning behind alternative emission control strategies, the expected impact on local air quality, the acceptable level of increase in emissions, possible technical abatement options and a detection method. In chapter five the same exercise is repeated for petrol-powered vehicles. Then, in chapter six, some general testing principles are drafted to detect these situations with possibly elevated emissions. Finally, in chapter seven an outlook is given regarding developments for the monitoring of real-world emissions.

2 Type approval risks versus risks over the lifetime of a vehicle

The aim of this report is to identify elevated emissions outside the boundaries of RDE legislation. Therefore, the focus of this report is on situations where RDE boundary conditions may be exceeded. However, elevated emissions are also possible in situations which are related to other parts of the regulated emission checks. Figure 2 provides an overview of the regulated checks for tailpipe emissions during the lifetime of a vehicle. The figure distinguishes the following aspects:

– The main responsible parties;
– Type of test: Laboratory (chassis dynamometer), on-road or other;
– Vehicle condition: in-service vehicles or not, i.e. used in real-world circumstances or not;
– Type of emission check;
– The potential risks for elevated emissions in real-world circumstances.

The figure shows that the set of regulated emission checks is a very comprehensive package. It also shows that the emission checks are a shared responsibility over different parties. However, every stage of the emission checks yields its own potential risk for elevated emissions. On the other hand, the main risks of the laboratory testing are covered by RDE. Therefore, the risks for RDE, and beyond RDE, have a clear relevance to on-road emission performance.

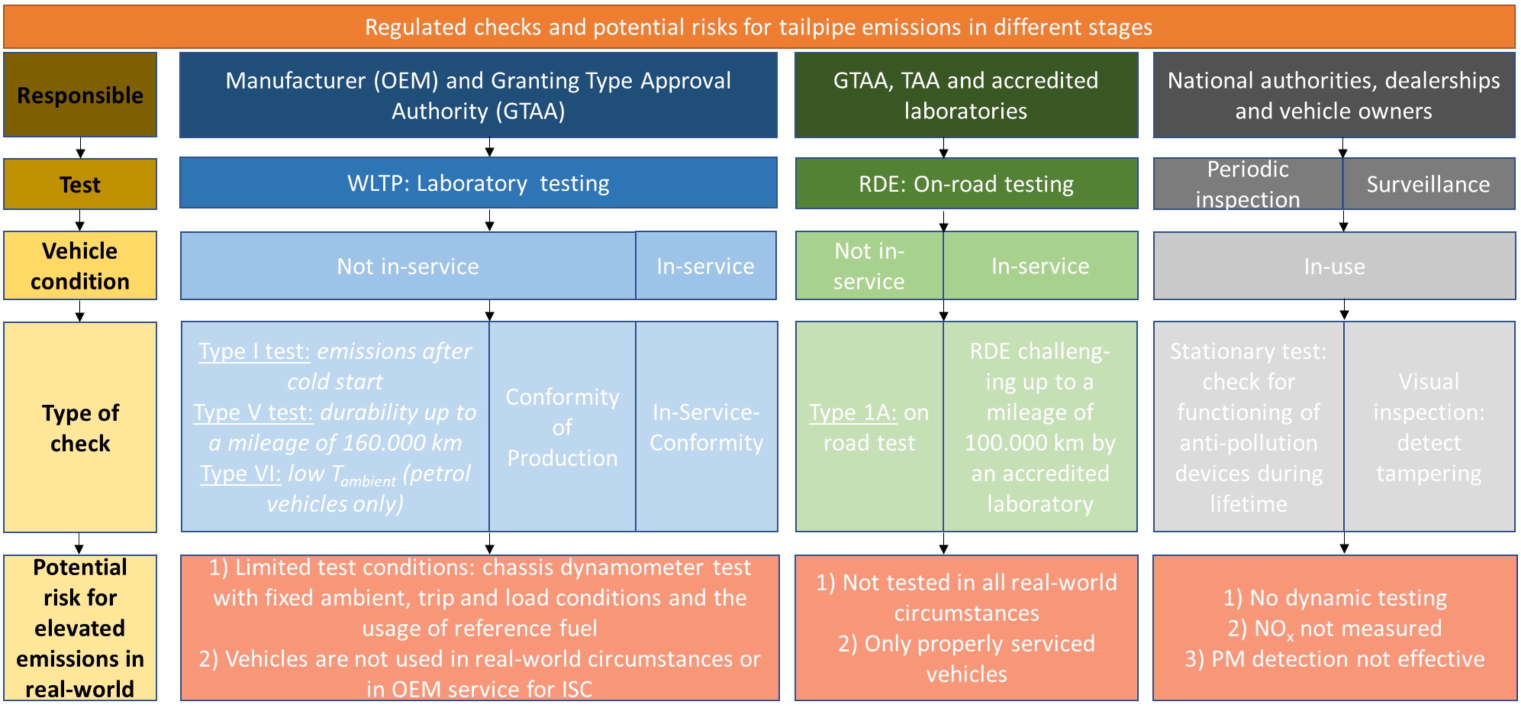

Figure 2: Type approval risks versus risks over lifetime.

The average real-world emissions of a vehicle depend on many parameters, like the design criteria of the vehicle in the development phase, the condition of the vehicle, the driving conditions, the road and ambient conditions, the driving behaviour and the kind of trip. The bandwidths of the type approval do not cover all these real-world conditions. Figure 3 below illustrates, as an example, the average real-world emissions of a vehicle as function of various risks during different stages of the lifetime of a vehicle. This figure illustrate that elevated emissions may occur in different stages of the vehicle's lifetime. These elevated emissions can occur in a stage where type approval limits still apply, but also in stages where only national periodic inspection and surveillance, which have a limited effectiveness for pollutant emissions, are in place. The latter is basically related to actions of vehicle owners, dealerships and other kind of car workshops. Elevated emissions may occur during every kind of driving condition when, for example, the vehicle is tampered with. As these situations are not detected in the type approval process, it is important to have a more effective periodic inspection or an effective surveillance in place. Elevated emissions which occur due to driving conditions which are outside the RDE boundaries, are less straightforward as they are related to the emission control strategy of a vehicle in specific situations. Therefore, this report aims to identify these potential situations and to identify the possible emission behaviour in these identified situations.

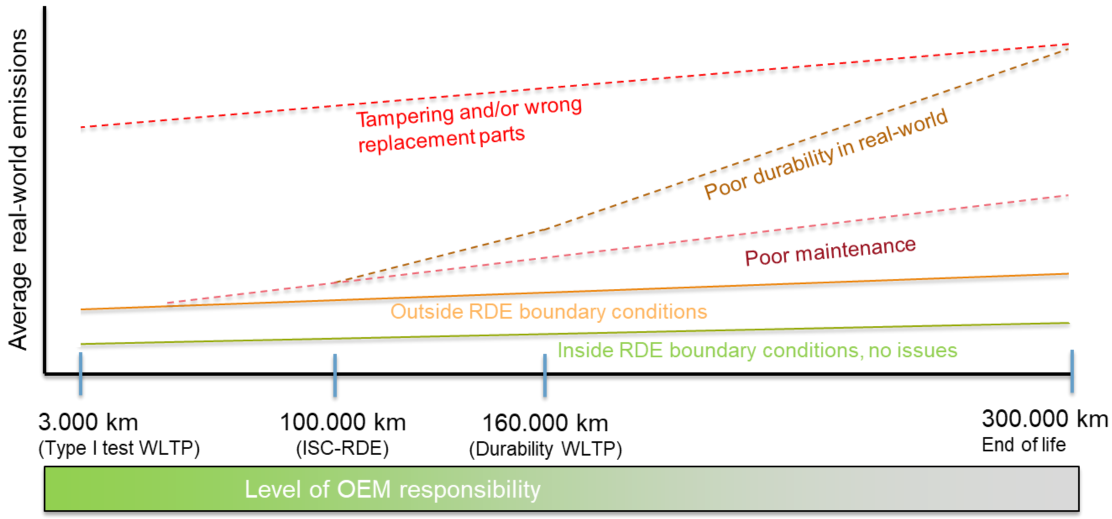

Figure 3: Illustration of average real-world emissions of a vehicle as function of various risks during different stages of the lifetime of a vehicle. Please note that the size of each area is not indicative of the real contribution of each risk, but only an illustration.

RDE legislation

Between 2015 and 2017 the Commission adopted three acts on Real Driving Emissions (RDE) (Commission Regulations (EU) 2016/427, (EU) 2016/646 and (EU) 2017/1154) introducing a new methodology for testing vehicle emissions in real-driving conditions. With these acts, the importance of using a test performed on the road is recognised as supplementary to the World-wide Light duty Test Procedure (WLTP), i.e. the laboratory test, in the context of type approval regulation for light-duty vehicles. On 3 May 2018 the Technical Committee of Motor Vehicles (TCMV) has voted positively the 4th part of the RDE regulation (RDE4). The new regulation is expected to be in force on the 1 January 2019. It contains the upgraded methodology for the RDE tests as well the procedures for testing emissions during in-service conformity (ISC) checks and additions with regard to the AES assessment.

RDE legislation is meant to secure pollutant exhaust emissions below the limit in many real-world circumstances which were considered by the legislator to depict the normal conditions of use. However, in specific situations, the real-world vehicle emissions may not benefit fully from RDE legislation. Boundaries for the test and vehicle conditions are specified within the RDE legislation, these boundaries are described in more detail in the next chapter. RDE conditions were never meant to cover all situations that might occur when driving on European roads. The general thinking was that each boundary condition would cover 95% of the full range of use. This means that 95% of all kilometres driven on European roads is expected to occur within the 0 to 30 ˚C range of RDE (and the extended range from -7 to 35ºC). The same applies for driving dynamics, altitude gain, and other aspects. Hence, eventually less than 95% of all driving may be within the combined boundaries and therefore be covered by RDE. It is in part the independent testing which should seek out the critical boundaries of RDE testing to achieve the maximal coverage possible with RDE testing.

The fact that there are boundary conditions automatically means that there are driving conditions which are not directly covered by the RDE test procedure. As a consequence, there is a potential risk that elevated emissions occur during these conditions due to emission control strategies that deviate to what is applied within the boundaries of RDE testing. In such a case, such strategies might indicate the activation of an AES (declared or not).

Assessment of AES
Article 2, points 43 and 42, of Commission Regulation (EU) No 692/2008, as amended by Commission Regulation (EU) No 2016/646, *defines **AES** and **BES** as follows*:

> *'43. 'base emission strategy' (hereinafter 'BES') means an emission strategy that is active throughout the speed and load operating range of the vehicle unless an auxiliary emission strategy is activated;*
>
> *44. 'auxiliary emission strategy' (hereinafter 'AES') means an emission strategy that becomes active and replaces or modifies a BES for a specific purpose and in response to a specific set of ambient or operating conditions and only remains operational as long as those conditions exist.'.*

These exceptional circumstances should be considered as situations where for good reasons some leeway may be given. For example, if situations occur only in a very small fraction of the time or the increase in emissions are minor, such that the overall, or average, effect on the emissions is 1% or less, some leniency may be given. In practice, there must be a balance between the risk of high emissions and impact of the technology needed to avoid it. In RDE legislation this has been a general principle all along. A focus on emission reductions under RDE conditions only, might, next to the rationale for AES and BES, also be in conflict with the general principle in emission legislation set out in article 5(1) of the Euro 5/6 regulation:

"*The manufacturer shall equip vehicles so that the components likely to affect emissions are designed, constructed and assembled so as to enable the vehicle, in normal use, to comply with this Regulation and its implementing measures."*

The manufacturer needs to report every AES in detail to the GTAA by an “Extended Documentation Package”, which is described in Appendix 3a of Annex I in Regulation (EU) 2017/1151. To avoid a very extensive documentation package, a limitation is of 100 pages is set, however, including annexes the limit of 100 pages may exceeded. When an AES is modified, the documentation package should be updated. An important aspect of the extended documentation package, which is directly related to exhaust emissions, is the following text in Appendix 3a of Annex I: “*(i) an evaluation of how the AES will control real-driving emissions to the lowest practical level, including a detailed analysis of the expected increase of total regulated pollutants and* CO_2*-emissions by using the AES, compared to the BES.*”

Moreover, in Appendix 3b of Regulation (EU) 2017/1151 a “Methodology for the assessment of AES” is added. The methodology describes the minimum verifications a GTAA should perform during an AES assessment. Most of the verifications are related to the reasoning of the application of an AES. The prescribed verification step which is directly related to the impact on exhaust emissions is described as follows:
“*(1) The increase of emissions induced by the AES shall be kept at the lowest possible level:*
(a) The increase of total emissions when using an AES shall be kept at the lowest possible level throughout the normal use and life of the vehicles;
(b) Whenever a technology or design that would allow for improved emission control is available on the market at the time of the AES preliminary assessment it shall be used with no unjustified modulation”

In addition, the Type-Approval Authorities Expert Group (TAAEG) shall compile a list of non-acceptable AES. This list will be made public by the Commission. Such a list will help to recognize a non-acceptable AES more easily.

The abovementioned text clearly shows that the RDE legislation does not only aims for lowering the emissions within the specified RDE boundary conditions but beyond these conditions as well. Moreover, this information serves as a guideline for the TAA in the assessment of AES. However, whereas the quantitative assessment of emissions within the RDE boundary conditions are described in very much detail, the assessment of emissions outside the boundary conditions of RDE is not specific and might be more qualitative rather than quantitative. With a non-specific or administrative assessment there still is a potential risk for elevated emissions in certain circumstances.

In-Service-Conformity & market surveillance
As mentioned above, procedures for testing emissions during in-service conformity (ISC) will be introduced with RDE4. These ISC tests are required in order to ensure that the real driving emissions are also effectively limited during the normal life of the vehicles under normal conditions of use. Moreover, in May 2018 Regulation (EU) 2018/858 with regard to market surveillance has come into force. An important part this regulation is point (36):
“*In order to support Member States in the task of detecting defeat devices, the Commission published, on 26 January 2017, Guidance on the evaluation of Auxiliary Emission Strategies and the presence of Defeat Devices with regard to the application of Regulation (EC) No 715/2007 on type approval of motor vehicles with respect to emissions from light passenger and commercial vehicles (Euro 5 and*

Euro 6). Consistent with that Guidance, the test activities of the Commission, of the type-approval authorities and of the technical services for the purpose of detecting defeat devices should remain non-predictable in character, and should also include modified testing conditions which entail variations in physical conditions and testing parameters."

ISC tests can be performed by accredited laboratories. Independent ISC testing, will form the bridge between the old world of type-approval authorities and the manufacturers, and the new world of testing under public scrutiny. But independent laboratories will have to follow strict rules in order not to disqualify the findings. Moreover, independent testing seems hampered as up to ten different vehicles may need to be sourced and tested to finalize a program. The results need to be discussed in detail with GTAA that has a vested interested because it has issued the original type approval. Furthermore, independent laboratories are not allowed to publicly report until the Granting Type-Approval Authority has published their report, which may be a year after the facts.

Independent ISC-testing programs should be embedded in proper financing schemes, in order to secure sufficient volume and that critical tests should be performed by independent laboratories. A valid RDE tests performed during type approval might fulfill the basic testing requirements. However, they might not reveal problems with elevated emissions of certain vehicle models. Therefore it is important to incorporate results and indications of monitoring programs or market surveillance tasks in the selection of vehicle specific critical tests.

With ISC in RDE4 together with the AES evaluation and the foreseen market surveillance, a decent legal basis to detect incompliance and secure low real-word emissions is set. To make it effective concrete implementation and enforcement are still required. In the current situation, there still are some risks that high real-world emissions occur and are not always detected.

3 RDE conditions

In this chapter the most important RDE test and vehicle conditions are described in brief. As these constitute limitations for RDE testing, the conditions are summarized as RDE boundaries This study aims to identify potential situations outside the scope of the RDE boundaries. Hence, it is useful to have a clear picture of spectrum of driving situations that is included in the conditions for a valid RDE test. The following conditions apply to RDE1-3 and might not reflect fully the state of play in RDE4, which was not adopted at the time of this publication.

The RDE boundaries are an integral part of the overall RDE legislation that consists of four consecutive steps:

1. Execution of a valid RDE on-road trip
A trip is valid if the driving conditions are within the windows defined in the legislation. Windows are defined for ambient conditions, road conditions, trip composition, driving behaviour and vehicle conditions.

2. Emissions measurement with PEMS equipment
Emissions will be measured during the RDE trip with PEMS equipment mounted in or to the vehicle. Naturally, the PEMS equipment and measurement procedure needs to fulfil certain legislative requirements.

3. Data processing and data evaluation
The PEMS measurement data will be processed by evaluation tools to take into account variations in severity of RDE trips and to normalize the RDE test results to the severity of a standard WLTP type-approval test. For hybrids the NO_x / CO_2 ratio is used to evaluate the measurement data. The evaluations tools are currently being evaluated. This may to changes in the data evaluation procedure in the near future.

4. Check against RDE emission criterion
The result of the data processing step will have to fulfil the RDE emission criterion. The vehicle will have to fulfil the criterion not only on the complete RDE trip, but also on the urban part of the trip.

As elevated may emissions occur also during the execution of a RDE trip, the afore-mentioned first step '*execution of a valid RDE on-road trip*' is relevant in the light of this study. Hence, in the paragraph that follows a brief overview is provided of the boundary conditions as prescribed in the RDE legislation on this matter.

3.1 Boundary conditions of a valid RDE on-road trip

In this chapter an overview is provided of several boundary conditions for the RDE test. An RDE trip executed within the normal and extended boundaries qualifies as valid. Emissions measured on a valid test must meet the RDE emission limits.

<u>Ambient temperature and road conditions</u>
Table 1 provides an overview of RDE boundaries for 'normal' driving, in terms of ambient and road conditions. This table makes a distinction between 'normal' and

‘extended’ boundary conditions. Under these extended conditions, it is more difficult to comply with the emission limits. Hence, the RDE legislation allows for a reduction factor of 1.6 for the emissions measured during driving events under extended conditions.

Table 1: Boundaries for ambient temperature and road conditions

Condition	**Boundaries**	
	Normal	**Extended**
Ambient temperature	0 - 30 °C Temporary[3]: 3 - 30 °C	-7 - 0 °C and 30 - 35 °C Temporary: -2 - 3 °C and 30 - 35 °C
Altitude	Maximum 700 m	Maximum 700 - 1300 m
Road surface	Paved road only	-
Road incline	Only indirectly restricted by maximum cumulative altitude gain over total RDE trip	-
(Head) wind, air pressure and air humidity	No restrictions	-

<u>Trip composition</u>
The RDE legislation contains several requirements for the composition of a valid RDE trip setting boundaries on the duration of the trip, the sequence of urban, rural and motorway driving, the minimum trip length and the number and duration of vehicle stops. Table 2 provides an overview of these boundaries for the trip composition.

[3] Temporary boundary conditions apply till 1 September 2019 for new type approvals and 1 September 2020 for all registrations.

Table 2: Boundary conditions for the trip composition

Condition	**Boundaries**	**Margins**
Duration	90 - 120 minutes	-
Shares of Urban (U), Rural (R) and Motorway (M) driving[4]	Resp. 34%, 33%, 33% of trip distance	29% ≤ U ≤ 44% 23% ≤ R ≤ 43% 23% ≤ M ≤ 43%
Sequence is fixed: Urban driving followed by Rural and Motorway driving	-	-
Length of each section (U/R/M)	At least 16 km	-
Cold or hot start	Maximum of 15 seconds idling after initial engine start and a limitation of 90 seconds in total for vehicle stop(s) in the entire cold start period of at most 5 minutes.	-
Stops (speed < 1 km/h)	Several stops ≥ 10 s may be included. Total stoppage time shall be 6 - 30% of time of urban driving. Stop shall not exceed 300 s.	-
Total cumulative positive altitude gain	< 1200 m per 100 km RDE trip distance, calculated over the full RDE trip. Road incline as such is not regulated.	-
Altitude start and end point	Shall not differ by more than 100 m.	-

Driving behaviour

The RDE legislation contains several requirements for the driving behaviour to prevent a valid RDE trip from consistently being driven extremely aggressive or extremely smooth. Table 3 provides an overview of the boundaries of ‘normal’ driving, in terms of driving behaviour.

A high value for $v * a_{pos}$, the product of vehicle speed and (positive) acceleration, is commonly used as an indicator for high(er) dynamics of a trip, while a low value for RPA, the relative positive acceleration, is an indicator for the lack of dynamics in a trip. Figure 4 shows $v * a_{pos}$ values for typical driving behaviour in the Netherlands, compared the RDE limit per road section.

[4] Urban driving is defined as all events with vehicle speed up to 60 km/h included, rural driving by speeds between 60 and 90 km/h and motorway driving by speeds above 90 km/h.

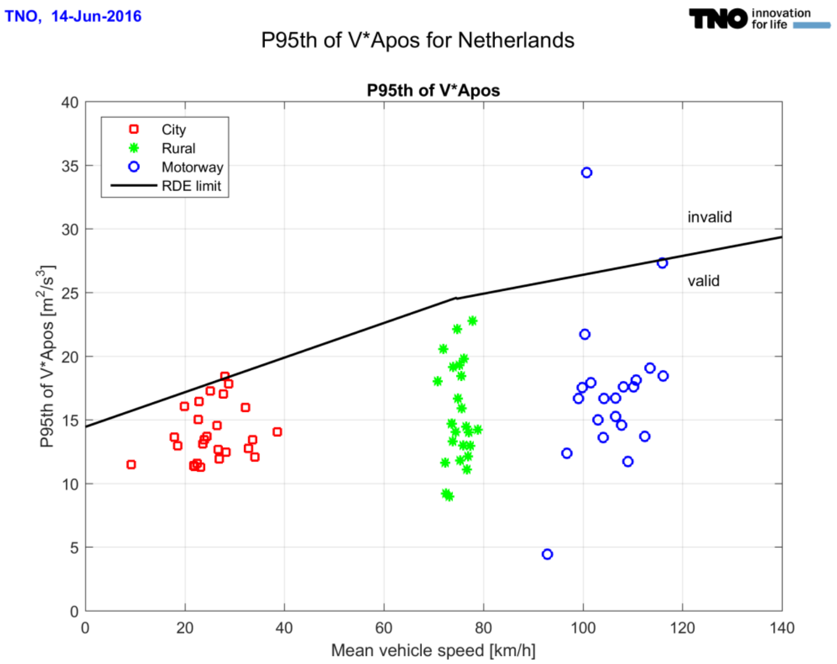

Figure 4: v * a_{pos} values for typical driving behaviour in the Netherlands per road section [1]

Table 3: Boundary conditions for driving behaviour

Parameter	**Boundaries**	**Comment**
v * a_{pos}	RDE trip is invalid if (per speed bin k with $k = 1{,}2{,}3$ for $0 - 60, 60 - 90, \text{resp.} > 90$ km/h) $\bar{v}_k \leq 74.6$ km/h and $(v \cdot a_{pos})_{k}[95] > (0.136 \cdot \bar{v}_k + 14.44)$ or $\bar{v}_k > 74.6$ km/h and $(v \cdot a_{pos})_k[95] > (0.0742 \cdot \bar{v}_k + 18.966)$	To exclude extremely high dynamics
RPA	RDE trip is invalid if (per speed bin) $\bar{v}_k \leq 94.05$ km/h and $RPA_k < (-0.0016 \cdot \bar{v}_k + 0.1755)$ or $\bar{v}_k > 94.05$ km/h and $RPA_k < 0.025$	To include sufficient dynamics
Average speed during urban driving	$15\ \text{km/h} \leq \bar{v}_{urban} \leq 40\ \text{km/h}$	
Maximum speed	$v_{max} \leq 145\ \text{km/h}$	For no more than 3% of the duration of motorway driving speeds up to 160 km/h are allowed.
Speed range of motorway driving	Shall properly cover a range between 90 and at least 110 km/h. Speed shall be above 100 km/h for at least 5 minutes.	Vehicles with speed limitations have modified boundaries.
Gear selection	No restrictions	

Vehicle conditions

The RDE legislation contains several requirements for the condition of the test vehicle prior to or during the RDE test. Table 4 provides an overview of the vehicle condition requirements.

Table 4: Boundaries for vehicle conditions

Parameter	Condition
Air conditioning systems and other auxiliary devices	Operation shall correspond to possible use by a consumer at real driving on the road.
Fuels, lubricants and reagents	Within specifications issued by the manufacturer for vehicle operation by the customer.
Payload	Besides the driver, a witness, test equipment and power supply, artificial payload may be added (up to 90% of the maximum payload).
Preconditioning	Driven for at least 30 minutes, then engine off for 6 to 56 hours.

Apart from the specified conditioning, the vehicle must be in a proper state. Hence, a proper maintenance record should be available. Moreover, the vehicle should not have active OBD (On-Board-Diagnostics) errors.

4 Possible situations of diesel vehicles with elevated NO_x emissions which are not covered by RDE conditions

In this chapter, a range of situations with possibly elevated emissions of diesel vehicles is identified. This is to be considered a non-exhaustive overview. The identified situations are divided in the categories as described below. Each category is described in a separate paragraph:
- Ambient and road conditions;
- Trip composition;
- Driving behaviour;
- Vehicle conditions.

For each identified situation with possibly elevated emissions, the aspects below are considered. The assessment of these aspects is based on expert judgement of the authors, augmented with input from the stakeholder consultations:
- The possible emission behaviour in the identified situations and examples of possible technical reasonings for this behaviour:
  - Next to expert judgement and inputs from stakeholder consultation reflecting future technologies in line with RDE, this report is also based on experiences with current technology and the problems encountered with high emissions;
  - In several public statements manufacturers have motivated certain choices regarding the balance between engine protection and emission control;
  - Given the fact that RDE4 is not in place, this a is non-exhaustive overview;
- The expected impact on local air quality;
- A suggestion for the acceptable and/or maximum increase in emissions, in the opinion of the authors;
- Possible technical mitigation options and some examples;
  - This also is non-exhaustive overview;
- Possible test or detection method(s).

The identified situations can occur in countless combinations during real-world driving. The combined impacts have not yet been assessed.

However, before these situations are described, additional context is provided by considerations on the possible trade-offs between low NO_x emissions and other vehicle aspects.

4.1 Trade-off between low NOx emissions and other vehicle aspects

In many cases NO_x reduction is not achieved by an isolated single change to a vehicle. There often is a certain trade-off between achieving low NO_x emissions and other aspects of engine and vehicle design. To minimize such trade-offs efforts may be made to optimize the emission control strategy in order to fulfil with the RDE legislation rather than to achieve low emissions under all real-world conditions. The following aspects are examples which can be in competition with the application of NO_x reduction technologies. These examples are not necessarily applied or even considered by a manufacturer.

Fuel economy and particle emissions

Some examples:

- Regenerations of the NO_x storage catalyst cause an increase in fuel consumption;
- Use of an enhanced fuel injection strategy. This can lead to an improved fuel economy, lower particle emissions and lower combustion noise. However, it can also cause increased NO_x emissions due to higher combustion flame temperatures;
- The use of EGR (Exhaust Gas Recirculation) can lead to a fuel penalty as EGR causes an increase in soot emissions. Due to this increase the DPF (Diesel Particulate Filter) may cause higher backpressures and a need for more frequent regeneration, both leading to a higher fuel consumption.
  Cooling is needed as well for EGR. To have sufficient cooling at high engine loads and EGR rates additional heat exchange may be needed. However, for a low fuel consumption, the effective heat exchange on the vehicle is often minimized, especially for passenger cars.
- The urban use of SCR for passenger cars may require some thermal management to retain SCR operating temperature at the cost of fuel.

Engine and catalyst durability

Some examples:

- EGR causes contamination within the engine and the EGR system itself. With higher EGR rates, the contamination will be higher as well.
- Every regeneration of the NO_x storage catalyst cause deterioration of the catalyst.

Investment and usage costs

Costs are involved to reduce NO_x emissions, both in terms of investments and additional costs throughout the vehicle's lifetime during usage. Some examples:

- Investments:
  - In order to reach low emissions in real-world circumstances enhanced emission control strategies are needed, such as a NO_x storage catalyst or an SCR (Selective Catalytic Reduction). The choice of certain technologies can vary for different types of cars.
- Vehicle lifetime costs:
  - EGR causes contamination within the engine and EGR system. Also, extra and more persistent particle emissions are produced. This will increase the maintenance costs. Moreover, engine malfunctions can lead to (expensive) compensation claims or recalls.
  - An SCR system needs urea. If more NO_x needs to be converted, more urea is needed. Technically an SCR catalyst can be developed to convert very high levels of NO_x emissions. However, this will have an effect on the costs for the user since the urea consumption will be high as well.

The aforementioned aspects should not be considered a license to switch off emission control systems when the vehicle is operated in conditions which are not covered by the RDE legislation. At minimum, the vehicles should make the best possible use of the applied technologies on the vehicle. If the technologies are partly or fully deactivated under conditions not covered by RDE, clear justification and evidence should be supplied by the vehicle manufacturer during type approval.

4.2 Ambient and road conditions

Based on the set boundaries for ambient and road conditions as shown in Table 1 in the previous chapter, the following possible situations with potentially elevated emissions are identified:

- Driving or conditioning in ambient temperatures (T_{amb}) lower than -7 ˚C;
  - Under cold ambient conditions the temperature is possibly not the only reason of an invalid RDE test, the boundaries for driving behaviour can be a reason as well. As the road can be covered with snow and ice, certain speed requirements may not be met;
- Cold start in ambient temperatures lower than -7 ˚C;
- Driving in ambient temperatures higher than 35 ˚C;
- Driving at altitudes higher than 1300 meter.

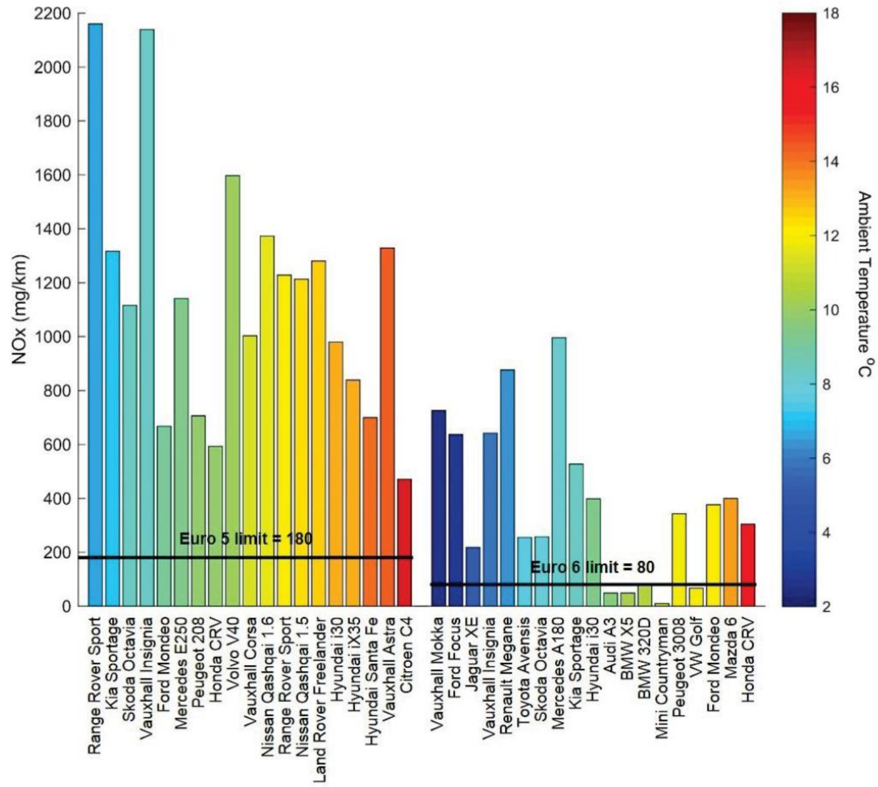

Figure 5: NO_x results from the recently published UK Vehicle Testing Programme.[5] Track test results plotted in order of increasing ambient temperature.

In particular, ambient temperatures can have a significant influence on NO_x emissions, as clearly indicated in Figure 5. It should, however, be noted that the tested vehicles are not type approved under the RDE legislation and that these kinds of ambient temperatures did not occur during their type approval process. Therefore, it is expected that vehicles which are RDE type approved, do not have elevated emissions to such an extent within the temperature range as specified in the RDE legislation. However, it is possible that elevated emissions occur outside the ambient temperature boundaries of RDE legislation. This risk is also present for the effect of a higher altitude. However, given the relatively wide RDE scope on

[5] http://www.unece.org/fileadmin/DAM/trans/doc/2015/wp29grpe/GRPE-73-03.pdf

ambient and road conditions, it depends on the common conditions in specific member states how relevant these situations are.

In Table 5 the identified situations are elaborated in more detail.

Table 5: Possible ambient/road conditions with potentially elevated emissions of diesel vehicles

Situation	**Possible behaviour (B) and examples of the technical reasoning (R) for elevated emissions**	**Expected impact on local air quality**	**Acceptable and/or maximum emissions increase**	**Examples of possible technical abatement options**	**Possible test or detection method(s)**
T_{amb} < -7 ˚C during driving or conditioning	**B:** Modified EGR rate **R:** Reduce the risk of condensation in inlet manifold and EGR intercooler **R:** Lower internal contamination of the engine **B:** No AdBlue injection **R:** Insufficient heat in exhaust gas for urea conversion to ammonia **R**: AdBlue free at -11°C **R:** Urea crystallization in SCR manifold **B:** Adapted injection strategy **R:** Compensation for low intake air temperature and improve fuel economy	High emissions in cold winter times on all road types	Reciprocal with the ambient temperature decrease every 7 ˚C starting from -7 ˚C. Additional reduction factor of 1.6[6] every 7 ˚C lower.	Feasibility of the following measures is already shown in heavy-duty vehicles: **+** Alternative or additional emission control system/ strategy, e.g. NO_x storage catalyst for low exhaust temperatures, gaseous ammonia in SCR system, closed coupled SCR/DPF, or water injection[7] **+** Improved temperature management, like improved insulation and rerouting air flow **+** (Mild) hybridization to avoid long idling periods which cool down the catalyst **+** Improved fuel injector quality to reduce soot emissions	**+** On road test in a cold area where the ambient temperature is < -7 ˚C **+** Test laboratory with temperature management **+** Screening test (NO_x/CO_2) in cool cell at idle condition to detect a temperature dependent switch
Cold start at T_{amb} < -7 ˚C	**B:** Alternative cold start strategy without fast warm-up of catalysts **R:** Focus on engine warm-up instead of catalyst warm-up and to improve combustion stability and avoid misfire	High emissions in cold winter times on urban roads		**+** Same as above-mentioned **+** Electric catalyst heating	
T_{amb} > 35 ˚C	**B:** Modified EGR rate and different engine operation (e.g. different air/fuel ratio) **R:** Avoid overheating of engine **R:** Lower air density → lower air intake **R:** Lower oxygen level (only relevant at high altitudes) **R:** Lower internal contamination **B:** No or limited NO_x regenerations in NO_x storage catalyst → NO_x is passing the catalyst unconverted **R:** Catalyst temperature too high for proper NO_x storage or limited possibilities for regeneration due to higher engine loads.	High emissions in warm summer times on all road types	At disproportionate high engine loads and ambient temperatures of > 35 ˚C or altitudes of > 1300 meter, an additional reduction factor based on CO_2 emission rate[8] may be applied.	**+** Alternative or additional emission control system/strategy e.g. SCR, or water injection **+** Improved design for temperature management, like an improved EGR cooler, two-stage EGR cooling and an increased engine cooling capacity **+** (Mild) hybridization for electric boost to assist engine during firm accelerations **+** Improved fuel injector quality to reduce soot emissions	**+** On road test in a warm area where the ambient temperature is > 35 ˚C **+** Use test laboratory with temperature management **+** Test with pre-heated inlet air
Altitude: >1300 meter		High emissions in mountain regions on urban and rural road types			**+** On road test in an area with altitudes of > 1300 meters **+** Use test laboratory with ambient pressure management

[6] As an extended use of the existing reduction factor of 1.6 for the extended conditions, see subsection 2.1.
[7] Water injection is still in development stage, with possible durability issues.
[8] An example of an additional reduction factor could be: Average CO_2 emission rate over a complete trip divided by two times the average WLTC CO_2 emission rate. Then, this reduction factor may be applied on the NO_x emissions. This reduction factor is also possible for separate road sections in combination with the corresponding WLTC subsection values, e.g. urban or motorway.

4.3 Trip composition

Based on the set boundary conditions for trip composition as shown in Table 2 in the previous chapter, augmented with some non-specified conditions, the following possible situations with potentially elevated emissions are identified:

- More than 15 seconds of idling after initial engine start, more than 90 seconds of vehicle stop in the cold start period and more than 300 seconds of idling:
  - The limitation of idling to a maximum of five minutes in the RDE test is a restriction of the test with respect to normal use. For example, many motorists keep the engine idling for long periods at movable bridges where vehicles must wait for the passage of ships. Other examples are taxis which are waiting for passengers, traffic jams or waiting for traffic lights in urban rush hour. Having this restriction of five minutes idling in the test could mean after longer idling periods emissions may go up to typical engine out levels;
  - The same risk applies to the maximum of 15 seconds idling after engine start. For example, it is not unusual for motorist to set the navigation, or to remove ice from the car windows, after they have started the engine;
- Deviating trips or trip sections in time and/or distance and a deviating sequence of the road sections compared to the RDE trip:
  - In real-world circumstances the variations in trip composition are almost infinite. By prescribing the trip composition, there is a potential risk that vehicles are optimized towards the specific trip composition and/or duration. Moreover, emissions may be higher in specific road sections which are not evaluated separately, like the rural and/or the motorway part. An example of this (for a vehicle not type-approved under RDE legislation) is shown in Figure 6;
- Manual switch-off of the engine during an RDE trip or in real life multiple times:
  - By doing so, an optimized vehicle may ‘think’ that the test just started, while the vehicle is, for example, at the end of the urban or somewhere in the rural part;
- Total cumulative positive altitude gain of > 1200 meter per 100 km:
  - In some countries, it is difficult to drive a valid trip due to this boundary condition. Even in moderately hilly regions the cumulative altitude gain can be substantial;
- A difference of more than 100 meters in altitude between the end and the beginning of the trip:
  - This might be relevant when mainly up- or downhill driving occurs during trips in regions with mountains.

In Table 6 the identified situations are elaborated in more detail.

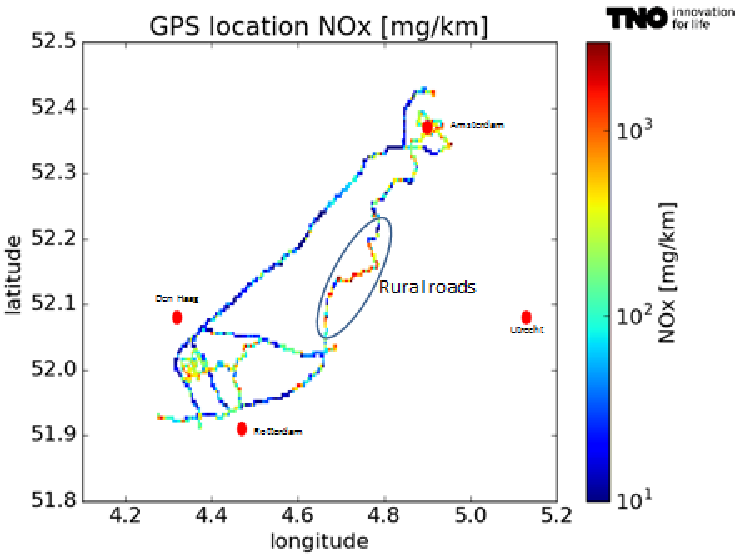

Figure 6: Emission measurement results of a modern Euro-6c diesel passenger car plotted on a real-world trip. The car showed good performance during driving on motorways with speed limits in force and expectedly higher emissions in urban areas. Emission performance during rural driving varied strongly. Source: TNO report: ‘TNO 2016 R11227: Assessment of the strengths and weaknesses of the new Real Driving Emissions (RDE) test procedure’.

Table 6 Possible situations with potentially elevated emissions of diesel vehicles related to the RDE trip composition

Situation	Possible behaviour (B) and examples of the technical reasoning (R) for elevated emissions	Expected impact on local air-quality	Acceptable and/or maximum emissions increase	Examples of possible technical abatement options	Possible test or detection method(s)
> 15 sec idling after initial engine start **> 90 sec vehicle stop in cold start period** **> 300 sec idling** **Total trip > 120 minutes** **Urban driving > 90 minutes** **Alternative road section sequence** **Motorway driving > 30 minutes** **Alternative distance shares per road section** **Manual engine switch off during trip**	**B:** Modified EGR rate and/or AdBlue injection **B:** Uncontrolled or missing regenerations in NO_x storage catalyst **B:** Application of poor quality or lower volume catalysts **B:** Alternative temperature management **R:** Efforts to optimize the emission control strategy in order to comply with the RDE legislation rather than achieving low emissions under all real-world conditions.	High emissions on all road types	No significant increase compared to the RDE limits	Efforts to optimize the emission control strategy for all reasonable real-world conditions	Drive an extra 'non-compliant' RDE trip in addition to the compliant RDE trip. The 'non-compliant' trip should include the following aspects: **+** 5 minutes idling after initial engine start and multiple idling phases of more than 10 minutes **+** A random sequence different from U/R/M with deviating distance shares for one or more road sections. For example, a more than one hour test drive at the highway or a one-and-a-half-hour test drive in an urban area. Or, a trip longer than 120 minutes. **+** Manually switching off the engine multiple times during idling phases.
Total cumulative positive altitude gain > 1200 m per 100 km	<u>Uphill driving:</u> **B:** Modified EGR rate and different engine operation (e.g. different A/F ratio) **B:** No or limited NO_x regenerations in NO_x storage catalyst → NO_x is passing the catalyst unconverted **R:** Engine power needed **R:** Avoid overheating of the engine: control strategies focused on reducing temperature **R:** Lower internal contamination **R:** Temperatures in engine and exhaust outside normal operation range	High emissions in mountain regions on urban and rural road types	**+** If end is lower than start: no increase allowed **+** If end is >100 m higher than start or the cumulative altitude gain is more than >1200 m per 100 km a reduction factor based on avg. CO_2 emission rate over complete trip[8]	<u>Uphill driving:</u> **+** Alternative or additional emission control system/ strategy e.g. SCR or water injection[6] **+** Improved design for temperature management, like an improved EGR cooler two-stage EGR cooling and an increased engine cooling capacity **+** (Mild) hybridization for electric boost to assist engine during firm accelerations **+** Improved fuel injector quality to reduce soot emissions <u>Downhill driving:</u>	**+** On road test in an area with significant altitude differences. For example, an uphill test can be evaluated separately from a downhill test. **+** Test laboratory with ambient pressure management

Situation	Possible behaviour (B) and examples of the technical reasoning (R) for elevated emissions	Expected impact on local air-quality	Acceptable and/or maximum emissions increase	Examples of possible technical abatement options	Possible test or detection method(s)
Altitude: > 100 m difference between start/end	**R:** Catalyst temperature too high for proper NO_x storage or limited possibilities for regeneration due to higher engine loads Downhill driving: **B:** No or limited AdBlue injection **B:** No regeneration in NO_x storage catalyst **R:** Insufficient heat in exhaust gas from motoring			**+** Alternative or additional emission control system/ strategy, e.g. gaseous ammonia in SCR system, closed coupled catalyst/DPF **+** Apply higher EGR rates **+** Improved temperature management, like improved insulation of the SCR and/or NO_x storage catalyst **+** Throttling or by-passing motoring exhaust gas flow in catalyst	

4.4 Driving behaviour

Based on the set boundary conditions for driving behaviour as shown in Table 3 in the previous chapter, augmented with some non-specified conditions, the following possible situations with potentially elevated emissions are identified:

- High engine loads due to high driving dynamics or motorway driving at high vehicle speeds:
  - Driving dynamics: Higher $v * a_{pos}$ (speed multiplied with positive acceleration) values than allowed according to the RDE legislation
    - As described in the report regarding strengths and weaknesses of the RDE legislation[1], the limits for $v * a_{pos}$ cover normal driving behaviour quite well. However, as driving behaviour and power-to-mass ratios of vehicles differ substantially, it is not necessarily unusual that higher driving dynamics occur during real-world circumstances. As an example, Figure 7 shows relatively high NO_x emissions during accelerations over a broad speed range;
  - Motorway driving at speeds higher than 145 km/h for relatively long periods:
    - This situation is particularly relevant for some German motorways without speed limitations. On these motorways, the vehicles are frequently operated for extended periods at speeds higher than 145 km/h;
- Traffic congestion on the motorway:
  - These traffic jams can cause an invalid RDE trip due to the RDE limitations of maximum test duration, minimum required distance and required average speed. Therefore, congestion is not very well covered within the RDE;
- Urban driving with an average speed lower than 15 km/h:
  - Stop-and-go traffic is frequently observed in densely populated areas with high traffic density. Stop-and-go urban traffic is generally associated with high emissions;
- Disable traction control and/or ESP (Electronic Stability Program). Or, enable special driving modes such as sportive or off-road modes:
  - These very specific kinds of systems may be disabled by aggressive/sportive motorists. In addition, drivers often have the possibility to choose different driving modes, like ‘eco’ or ‘sportive’ which are covered in RDE. On the other

hand, traction control and ESP, associated with racing, and special settings of the vehicle are not covered in RDE.

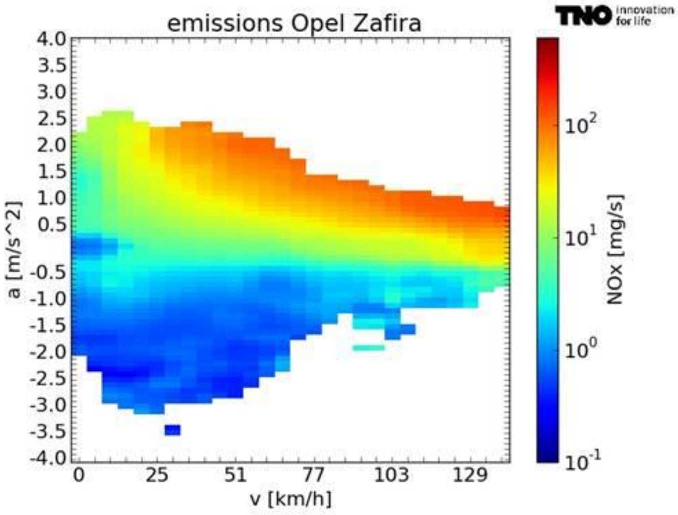

Figure 7: Typical emission map of a modern Euro 6 diesel passenger car, based on on-road emission measurements. Source: TNO 2016 R11177 "NO_x emissions of fifteen Euro 6 diesel cars: Results of the Dutch road vehicle emission testing program 2016", Heijne et.al.

In Table 7 the identified situations are elaborated in more detail.

Table 7: Possible situations with potentially elevated emissions of diesel vehicles related to the driving behaviour.

Situation	Possible behaviour (B) and examples of the technical reasoning (R) for elevated emissions	Expected impact on local air-quality	Acceptable and/or maximum emissions increase	Examples of possible technical mitigation options	Possible test or detection method(s)
v * a_{pos} [95] > RDE limit	**B:** Modified EGR rate and different engine operation (e.g. different A/F ratio) **B:** No or limited NO_x regenerations in NO_x storage catalyst → NO_x is passing the catalyst unconverted **B:** Modified AdBlue injection **R:** Engine power needed **R:** Avoid overheating of the engine: control strategies focused on reducing temperature **R:** Lower internal contamination **R:** Temperatures in engine and exhaust outside normal operation range **R:** Catalyst temperature and/or space velocities too high for proper NO_x storage or limited possibilities for regeneration due to higher engine loads	High emissions at high engine loads on all road types	At dispropor-tionate high engine loads, when RDE limits are exceeded, a reduction factor based on the CO_2 emission rate may be applied[8]	**+** Alternative or additional emission control system/ strategy like water injection[6] **+** Improved design for temperature management, like an improved EGR cooler, two-stage EGR cooling and an increased engine cooling capacity **+** Improved fuel injector quality to reduce soot emissions **+** Improved design SCR or NO_x storage catalyst to allow for higher space velocities and extra AdBlue injection (in case of SCR) **+** (Mild) hybridization for electric boost to assist engine during firm accelerations	
Motorway driving at > 145 km/h		High emissions at high engine loads on the motorway			

<table>
<tr><th>Situation</th><th>Possible behaviour (B) and examples of the technical reasoning (R) for elevated emissions</th><th>Expected impact on local air-quality</th><th>Acceptable and/or maximum emissions increase</th><th>Examples of possible technical mitigation options</th><th>Possible test or detection method(s)</th></tr>
<tr><td>Traffic congestion on the motorway</td><td rowspan="2">B: No or limited AdBlue injection
B: No regeneration in NO_x storage catalyst

R: Insufficient heat in exhaust gas</td><td>High emissions during congestion on the motorway</td><td rowspan="3">No increase acceptable</td><td rowspan="2">+ Alternative or additional emission control system /strategy e.g. gaseous ammonia in SCR system, closed coupled catalyst/DPF
+ Apply higher EGR rates
+ Improved temperature management, like improved insulation of the SCR and/or NO_x storage catalyst
+ Improve fuel injector quality to reduce soot emissions
+ (Mild) hybridization to avoid long idling and low load periods which cool down the catalyst</td><td rowspan="3">Drive an extra ‘non-compliant’ RDE trip in addition to the compliant RDE trip. The ‘non-compliant trip should include the following aspects:

+ Multiple firm accelerations at different vehicle speeds

+ Testing at the German highway at >145 km/h for more than 3% of duration of motorway driving

+ Testing in residential areas with speeds < 15 km/h

+ Testing on the Motorway during rush hour

+ Randomly switch off the engine multiple times

+ Switch off ESP and traction control for 10 minutes at each road type

Or, simulate the above-mentioned aspects and their valid RDE equivalents on a chassis dynamometer</td></tr>
<tr><td>v_{avg} urban driving < 15 km/h</td><td>High emissions in urban areas</td></tr>
<tr><td>Disable traction control and/or ESP or select special mode</td><td>Efforts to optimize the emission control strategy in order to comply with the RDE legislation rather than achieving low emission under all real-world conditions.</td><td>High emissions on all road types</td><td>Efforts to optimize the emission control strategy for all reasonable real-world conditions</td></tr>
</table>

4.5 Vehicle conditions

Based on the set specifications for vehicle conditions as described in the RDE legislation and in Regulation (EC) No 692/2008 (regarding emissions from light passenger and commercial vehicles (Euro 6)), augmented with some non-specified conditions, the following possible situations with potentially elevated emissions are identified:

- Towing a trailer or caravan, or using a roof rack or bicycle rack:
  - A typical but not exclusively Dutch situation, a family car towing a caravan. The total mileage of this type of driving is limited. It is not the vehicle conditions as such that exclude towing a caravan from valid RDE testing, but the boundaries for driving behaviour and the evaluation tools. The motorway speed requirement, that the RDE trip shall properly cover a range between 90 and at least 110 km/h and shall be above 100 km/h for at least 5 minutes, cannot be met. Moreover, the evaluation tools will simply exclude most events, because of the high CO_2 emissions;
- Driving a convertible with the roof open:
  - This can have a significant effect on the aerodynamics of the vehicle, in particular during highway driving;
- Fuel quality:
  - All market fuels, which fulfil the Fuel Quality Directive, i.e., a subset of the EN590 specifications, can be used in an RDE test. It is unknown whether all market fuels satisfy these requirements;
- Vehicle conditions with the result that the vehicle may be excluded from In-Service-Conformity (ISC) RDE testing, such as:
  - Odometer > 100.000 km:
    - For ISC testing the mileage of the vehicle should not exceed 100.000 km. However, according to Reg. 692/2008, the useful life of a vehicle is set to 160.000 km. Moreover, in real-world the lifetimes of modern vehicles are in general much higher. A mileage exceeding the RDE boundary of 100.000 km as such should not be a sufficient reason for elevated emissions;
  - Expired maintenance interval:
    - An expired maintenance interval is not a valid reason to have elevated emissions, except when there is a problem with the emission control system;
  - Non-intrusive OBD (On-Board-Diagnostics) error:
    - A non-intrusive OBD error is not a valid reason to have elevated emissions when this error is not related to the emission control system;
- Vehicle conditions which the vehicle may recognize as being RDE tested, such as:
  - OBD connected;
  - Rear window open or removed taillight;
  - Exhaust back pressure and/or load on the trailer hook due to PEMS installation;
  - A preconditioning of the vehicle which differs from the procedure in the legislation: ‘driven for at least 30 minutes, then engine off for 6 to 56 hours’.

RDE has been developed in such a way that the RDE tests can be performed independent of the vehicle: no OBD or ECU signals from the vehicle are required.

This limits the risk that the vehicle recognizes being RDE tested and is switched to a special engine control strategy.

In Table 8 the identified situations are elaborated in more detail.

Table 8: Possible situations with potentially elevated emissions of diesel vehicles related to vehicle conditions.

<table>
<tr><th>Situation</th><th>Possible behaviour (B) and examples of the technical reasoning (R) for elevated emissions</th><th>Expected impact on local air-quality</th><th>Acceptable and/or maximum emissions increase</th><th>Examples of possible technical abatement options</th><th>Possible test or detection method(s)</th></tr>
<tr><td>Towing a trailer or caravan, or using a roof rack or bicycle rack</td><td>B: Modified EGR rate and different engine operation (e.g. different A/F ratio)
B: No or limited NO_x regenerations in NO_x storage catalyst → NO_x is passing the catalyst unconverted
B: Modified AdBlue injection

R: Engine power needed R: Avoid overheating of the engine: control strategies focused on reducing temperature
R: Lower internal contamination
R: Temperatures in engine and exhaust outside normal operation range
R: Catalyst temperature and/or space velocities too high for proper NO_x storage or limited possibilities for regeneration due to higher engine loads</td><td>High emissions at high engine loads on motorways or on rural roads due to roundabouts or driving uphill</td><td>At disproportionate high engine loads a reduction factor based on the CO_2 emission rate may be applied[8] when a caravan/trailer is towed</td><td>+ Alternative or additional emission control system/ strategy like water injection[6]

+ Improved design for temperature management, like an improved EGR cooler, two-stage EGR cooling and an increased engine cooling capacity

+ Improved fuel injector quality to reduce soot emissions

+ Improved design SCR or NO_x storage catalyst to allow for higher space velocities and extra AdBlue injection (in case of SCR)

+ (Mild) hybridization for electric boost to assist engine during firm accelerations</td><td>Testing with caravan or trailer, or roof rack</td></tr>
<tr><td>Convertible with roof open</td><td rowspan="2">B: Modified EGR rate and/or AdBlue injection

R: Efforts to optimize the emission control strategy in order to comply with the RDE legislation rather than achieving low emissions under all real-world conditions.</td><td>In particular high emissions on the highway can be expected</td><td>No increase is acceptable</td><td rowspan="2">Efforts to optimize the emission control strategy for all reasonable real-world conditions</td><td>Driving with roof open</td></tr>
<tr><td>Fuel quality</td><td>High emissions at all road types</td><td>No increase is acceptable when fuel specifications meet the requirements of the Fuel Quality Directive and fuel standards</td><td>Use market fuel during test</td></tr>
</table>

Situation	**Possible behaviour (B) and examples of the technical reasoning (R) for elevated emissions**	**Expected impact on local air-quality**	**Acceptable and/or maximum emissions increase**	**Examples of possible technical abatement options**	**Possible test or detection method(s)**
Vehicle not valid for ISC emission testing		High emissions on all road types	**+** Only at a mileage of more than 160.000 km a higher CF may be applied: The existing durability factors can be extrapolated beyond the 160.000 to 320.000 km. As an alternative, modified durability factors can be developed, or the periodic inspection and servicing should ensure the appropriate state of the vehicle. **+** No emission increase is acceptable when the maintenance or OBD error is not related to the emission control system.	**+** Efforts to optimize the emission control strategy for all reasonable real-world conditions **+** The application of catalysts with an enhanced durability	Drive a regular RDE trip with a vehicle that has: **+** Driven > 100.000 km **+** An expired maintenance interval **+** Some OBD errors
Potential test recognition	**B:** Modified EGR rate and/or AdBlue injection **R:** Efforts to optimize the emission control strategy in order to comply with the RDE legislation rather than achieving low emissions under all real-world conditions.	High emissions on all road types	No increase is acceptable	Efforts to optimize the emission control strategy for all reasonable real-world conditions	Drive an extra ‘non-compliant’ RDE trip in addition to the compliant RDE trip. The ‘non-compliant trip should include the following aspects: **+** OBD connected **+** Rear window opened **+** Removed taillight **+** Different preconditioning

5 Possible situations of petrol vehicles with elevated emissions which are not covered by RDE legislation

In this chapter, considerations are provided on possible trade-offs between low emissions and other vehicle aspects. After, a range of situations with possibly elevated emissions of petrol vehicles is identified. This range of situations is to be considered a non-exhaustive overview. Moreover, the identified situations may occur in multiple combinations during real-world driving. The combined impacts have not yet been assessed. The assessment of these aspects is based on expert judgement of the authors, augmented with input from the stakeholder consultations

5.1 Trade-off between low emissions and other vehicle aspects

In chapter 4.1 trade-offs are given for modern diesel vehicles which describe the competition between low emissions versus other aspects of engine and vehicle design. For diesel vehicles quite some examples of possible trade-offs were given. In this paragraph the same exercise is made for petrol vehicles. If there are many trade-offs, the risks for elevated emissions may be higher.

The aspects below are examples which can be in competition with lowering the emissions. These examples are not necessarily applied or even considered by a manufacturer.

<u>Fuel economy</u>
- Petrol engines can be engineered with different air-fuel ratios.
  - Stoichiometric engines with normal air-fuel ratios (around 14.5) are equipped with three-way catalysts, this concept is commonly applied because the specific power of the engine is high and exhaust emissions of HC, CO, and NO_x can all be simultaneously controlled for very low levels. Due to the higher exhaust gas temperatures, the fuel efficiency is not optimal.
  - Lean-burn engines operate with air excess and a lower operating temperature and reduced throttling which yields higher fuel efficiencies. While engine-out NO_x decreases as air/fuel ratios increase above about 16.5:1, NO_x cannot be converted in the catalyst to harmless products because of the excess air.
- Catalyst brick configuration: a catalyst with a higher flow resistance increases the engine backpressure and fuel consumption;

<u>Investment and usage costs</u>
Investment costs are involved to reduce CO, HC, NO_x and PM/PN emissions. Some examples:

The three-way catalyst consists of precious metals which strongly determine its performance. The maximum exhaust gas temperature in a close coupled three-way catalyst can be more than 1000 °C. Lowering the maximum exhaust gas temperature decreases the thermal deterioration of the engine and catalyst which results in an extended durability. In particular at high engine loads for longer periods of time, high engine and exhaust temperatures may be an issue.

To lower the engine and exhaust gas temperatures, methods like a modified air-fuel ratio, or the application of an enhanced intercooler, EGR, variable valve timing and good misfire detection may be applied. However, such methods may yield additional engineering, hardware and usage costs. For example, in the case of a modified air-fuel ratio the fuel consumption may rise. In the case of EGR, higher maintenance costs can be expected due to contamination within the engine and the EGR system itself. Moreover, engine malfunctions can lead to (expensive) compensation claims or recalls.

As an alternative, higher quality components may be applied which are better resistant for high temperatures. Clearly, this would lead to increased engineering and investment costs, over alternative methods like temporary enrichment of the air fuel mixture.

Specifically, for lowering PN emissions, the application of a Gasoline Particulate Filter (GPF) can be considered. A GPF is a passive element with a relatively constant filtration efficiency and it is expected that real world PM/PN emissions will be low in all cases. However, PM/PN emission of GDI engines can also be optimised with other parameters like fuel injection pressures and patterns. A restricted optimisation of these parameters could be sufficient and reduce the investment costs.

Emission Impacts

To reduce engine and emission control system temperatures and to boost performance, gasoline vehicles are routinely programmed to switch to a rich air/fuel ratio at higher loads. Unfortunately, the emission impact is extremely non-linear. HC and CO catalyst conversion efficiency is reduced to very low levels, NO_x catalyst conversion efficiency is significantly decreased, and engine-out CO and PN emissions are proportional to the amount of enrichment. Due to the extremely high catalyst conversion efficiencies when gasoline engines run at stoichiometry, enrichment results in roughly an order of magnitude increase in HC emissions, two orders of magnitude increase in CO emissions, about very large increases in NO_x and PN emissions. These non-linear impacts mean that even a small amount of enrichment can easily double or triple real world emissions.

Enrichment is also needed to ensure enough fuel evaporates for proper combustion when the engine is cold after a start at temperatures below roughly 10˚C. This is primarily a concern for CO and PN emissions, as both CO and PN emissions are proportional to the amount of enrichment. Enrichment ends after the engine warms up to normal operating temperatures.

Conclusion
For diesel vehicles many of the described trade-offs in paragraph 4.1 are related to possible strategies for the emission control systems. These strategies may result in a lower effectiveness, or even deactivation, of the emission control systems in some conditions which are not covered by the RDE legislation. For petrol vehicles such strategies for the emission control system are not identified. The identified trade-offs for petrol vehicles are mainly related to the kind of applied engine and aftertreatment technologies. Still, there is a risk for elevated emissions outside the specified RDE conditions because certain technologies may be not fully effective in certain circumstances.

5.2 Possible situations with elevated emissions

In this paragraph possible situations with elevated emissions are identified for petrol vehicles. Due to the stronger link for diesel vehicles with possible specific emission control strategies, a separate table for each type of boundary condition is made for diesel vehicles in Chapter 4. The identified risks for elevated emissions of petrol vehicles are, as mentioned before, mainly related to the kind of applied technologies. Therefore, unlike the assessment for diesel vehicles, the boundary conditions are not taken as a starting point. At first, general circumstances and conditions were investigated where petrol vehicles, both direct injected and port fuel injected engines, may lead to elevated emissions. Then, based on the general circumstances and conditions, specific situations outside the prescribed boundary conditions are listed where elevated emissions may occur. All regulated emissions, i.e. CO, HC, NOx and particles are considered. The circumstances and conditions below are identified as the main causes for possible elevated emissions for petrol vehicles. The mentioned specific situations are explained in more detail in Chapter 4. Compared to the assessment for diesel vehicles no extra situations are added.

Cold ambient temperatures; relevant for PN, CO, and THC emissions:
- *Driving or conditioning in ambient temperatures (T_{amb}) lower than -7 ˚C;*
- *Cold start in ambient temperatures lower than -7 ˚C;*

- **Low engine loads;** relevant for CO, HC and NO_x emissions due to low exhaust gas temperatures:
  - *More than 15 seconds of idling after initial engine start, more than 90 seconds of vehicle stop in the cold start period and more than 300 seconds of idling*
  - *Total cumulative positive altitude gain of > 1200 meter per 100 km*
  - *Traffic congestion on the motorway*
  - *Urban driving with an average speed lower than 15 km/h*
  - *A difference of more than 100 meters in altitude between the end and the beginning of the trip: This might be relevant when substantial prolonged downhill driving occurs.*

- **High engine loads for longer time periods and peak engine loads;** relevant for all emissions of petrol engines.
  - *Motorway driving at speeds higher than 145 km/h for relatively long periods*
  - *Towing a trailer or caravan, or using a roof rack or bicycle rack:*
  - *Total cumulative positive altitude gain of > 1200 meter per 100 km and a difference of more than 100 meters in altitude between the end and the beginning of the trip: This might be relevant when substantial prolonged uphill driving occurs.*
  - *Driving dynamics: Higher v * a_{pos} (speed multiplied with positive acceleration) values than normally encountered during RDE driving events*

- **Other; may be relevant for all emissions**
  - *Vehicle conditions with the result that the vehicle may be excluded from In-Service-Conformity (ISC) RDE testing, such as:*
    - *Odometer > 100.000 km*
    - *Expired maintenance interval*
  - *Fuel quality;*

In Table 9 the identified situations are elaborated in more detail. The table is presented in a similar way, with the same columns, as for the assessment of diesel vehicles. However, the column ‘*Possible test or detection method(s)*’ is not displayed since this column would be identical to the corresponding column for diesel vehicles.

Table 9: Possible situations with potentially elevated emissions of petrol vehicles

Situation		**Possible behaviour (B) and examples of the technical reasoning (R) for elevated emissions**	**Expected impact on local air quality**	**Acceptable and/or maximum emissions increase**	**Examples of possible technical abatement options**
Cold ambient temperatures	T_{amb} < -7 ˚C during driving or conditioning	B: Adapted injection strategy R: inhomogeneity in air-fuel mixture due to incomplete evaporation[9] B: Different engine operation (e.g. deviation from stochiometric operation) R: Compensation for low intake air temperature and improve air-fuel mixing.	High THC, CO, & PN emissions in cold winter times in urban areas for both PFI and GDI engines	Reciprocal with the ambient temperature decrease every 7 ˚C starting from -7 ˚C. Additional reduction factor of 1.6[1] every 7 ˚C lower.	+ Improved temperature management, like heating of intake air flow + (Mild) hybridization to avoid long idling periods which cool down the catalyst + Close coupled catalyst + For starting: electric heating of the catalyst + Gasoline Particulate Filter + Improve fuel injection strategy to reduce soot emissions, like dual injection + Secondary air injection + Cylinder deactivation + Active Valve Control: Switch of thermodynamic cycle (Miller/Atkins cycle
	Cold start at T_{amb} < 10 ˚C	*Same as above, plus*: B: Alternative cold start strategy R: Focus on engine warm-up instead of catalyst warm-up and to improve combustion stability and avoid misfire B: Low catalyst temperature R: Insufficient heat in exhaust gas			
Low engine loads	> 15 sec idling after initial engine start	B: Low catalyst temperature R: Insufficient heat in exhaust gas	High CO, THC and NO_x emissions for both PFI and GDI engines	No increase acceptable	
	> 90 sec vehicle stop in cold start period				
	> 300 sec idling >				
	Traffic congestion on the motorway				
	vavg urban driving < 15 km/h				
	Prolonged downhill driving				
High engine loads for longer time periods	Motorway driving at > 145 km/h	B: Adapted injection strategy (pre-mix[10] → timed injection) B: Different engine operation (e.g. fuel enrichment) R: Engine power needed R: Avoid engine detonation or knock <u>Specifically for longer periods:</u> R: Avoid overheating of engine R: Avoid overheating of the catalyst: control strategies focused on reducing temperature	High HC, COemissions for all petrol engines at high engine loads on all road types, GDI additionally NO_x and PN emissions	At disproportionate high engine loads, when normal RDE driving limits are exceeded, a reduction factor based on the CO_2 emission rate may be applied	+ Improved temperature management, like an enhanced intercooler or an alternative position for the coolant radiator + Improved engine design and materials, like variable valve timing + Improve fuel injection strategy to reduce soot emissions + The application of catalysts with an enhanced durability + Gasoline Particulate Filter for PN emissions + (Mild) hybridization for electric boost to assist engine during firm accelerations + Water injection + Limit the engine power
	Towing a trailer or caravan, or using a roof rack or bicycle rack Convertible with roof open				
	Prolonged uphill driving				
Peak engine loads	v * apos [95] > normal RDE				
Other	Vehicle not valid for ISC emission testing	Efforts to optimize the emission control strategy and components in order to comply with the RDE legislation rather than achieving low emissions under all real-world conditions.	High emissions on all road types for all petrol passenger cars	No increase acceptable	Efforts to optimize the emission control strategy and components for all reasonable real-world conditions, and detect malfunctions with OBD
	Fuel quality				

[9] Low temperatures can cause inhomogeneity in the air-fuel mixture due to incomplete evaporation of the fuel in the inlet port or cylinder, depending on the type of engine.
[10] With pre-mix the air-fuel mixture has generally a better homogeneity than with timed injection.

6 General testing principles to identify elevated emissions

This chapter provides some general testing principles for the detection of (situations with) possible elevated emissions. However, a sound test procedure and data analysis should be more comprehensive. The paragraphs below provide a starting point only.

6.1 Risk based testing within the boundary conditions

Risk based testing is meant to recognize the situations where elevated emissions may occur. In an ideal situation, the first step would be to drive a regular RDE test with sufficient variation in driving behaviour. This RDE trip shall be compliant with the set boundary conditions. In the second step the trip data is analysed, and situations with clearly elevated emissions can be identified. A second, dedicated RDE test is driven as a third step. Also, this test shall be compliant with the boundary conditions. However, the trip should be designed such that situations where elevated emissions occur hold a prominent position in the test. For example, when a vehicle seems to have elevated emissions at low speed urban driving, these conditions can be emphasized during the RDE test.

As an alternative, when only one test can be executed, the risk of failure can be estimated based on the applied emission control technologies. For example, a vehicle with SCR may find low-power driving conditions difficult to cope with. Such driving conditions can be emphasized during the RDE test.

6.2 'Non-RDE-compliant' and additional specific real-world testing

A more extensive method of testing would be to drive one or more extra on-road tests in addition to a regular RDE trip. This method is meant to assess the vehicle's emission performance outside the scope of the RDE boundary conditions. The first step would be to drive a valid RDE trip which fulfils the RDE criteria. If all is well, the vehicle is being compliant with the emission limits. The second step is to drive an additional extended real-world trip where the situations outside the scope of the RDE legislation are assessed.

For example, this trip may include the aspects which were identified in the previous chapter:
- 5 minutes idling after initial engine start;
- Multiple idling phases of more than 10 minutes;
- Multiple firm accelerations at different vehicle speeds;
- Testing in residential areas with speeds < 15 km/h;
- A motorway trip with congestion;
- Longer periods of motorway driving;
- A complete test with a caravan or trailer;

Depending on the common ambient and road conditions in specific member states, the following aspects might be interesting to include in the test:
- Testing at ambient temperatures lower than -7 ˚C or higher than +35 ˚C;
- Testing at altitudes higher than 1300 meters;

- Testing with an altitude difference of more than more 100 meters between start and end;
- Testing at the German highway at speeds > 145 km/h for more than 3% of duration of motorway driving.

To identify possible efforts which are made to optimize the emission control strategy in order to comply with the RDE legislation rather than achieving low emissions in all real-world conditions, the following trip and vehicle aspects, for example, may be added:

- a random sequence different from U/R/M with deviating distance shares for one or more road sections. For example, a more than one hour test drive at the highway or a one-and-a-half-hour test drive in an urban area;
- Manually switch off the engine multiple times during idling phases;
- Switch off ESP and traction control for 10 minutes at each road type;
- OBD connected for some periods during the tests;
- Testing a vehicle with:
  - the rear window opened;
  - a removed taillight;
  - a mileage of >160.000 km;
  - an expired maintenance interval;
  - some active OBD errors.

When the trip data is analysed, it is important to check if the elevated emissions only occur during a specific situation, or that this situation works as a trigger. When it has worked as a trigger, emissions remain high during ‘RDE compliant’ situations as well (e.g. hysteresis in the system).

Another possible testing method is to use repetitions of short cycles, or parts of routes. Many emission control strategies contain an aspect of history or delay. This may in part be legitimated, for example, with a cold start or catalyst buffer. But in principle, the repetitions of short cycles, or parts of routes are a good method to examine history effects. A repetition of the same (short) route, with the same driving, should without history effects lead to similar emissions. Large variations, above the RDE limits, in the results of repeated trips are an indication of a complex emission control strategy warranting further investigations.

6.3 Monitoring

As an alternative for testing, monitoring is a very suitable method to detect high emissions in various real-world situations. With monitoring, emissions are measured during regular use of the vehicle throughout a period of multiple days, weeks or even months. All kind of real-world circumstances can occur in these longer periods. In an ideal situation, multiple vehicles of the same model are monitored. By doing so, the effect of different types of usage and driving behaviour can be assessed, and malfunctions and abuse separately assessed.

In the data analysis the situations where elevated emissions arise can be detected. Moreover, it can be determined if these elevated emissions occur one-off or repeatedly in relation to conditions that are inside or outside of the RDE boundaries.

Usually, the equipment used for monitoring is different than for regular on-road measurements. For official RDE testing a PEMS (Portable Emissions Measurement System) is used. The RDE legislation contains a full description of the PEMS equipment, its required quality and the measurement procedures. However, as a PEMS is expensive equipment, takes up quite some space and has an autonomy which is limited to a few hours. Moreover, it requires an operator and, therefore, it is not suitable for monitoring purposes. Therefore, a small sensor based data acquisition system is more practical for monitoring purposes. Moreover, such a system does not necessarily need to measure all regulated emission constituents. Instead, it can be limited to the most important parameters.

Compared to PEMS testing, monitoring can be cost effective. However, for legislative purposes PEMS equipment is required. Therefore, monitoring can also be used as a screening method to detect high emitting vehicles or situations with elevated emissions. When further investigation of a monitored vehicle is needed, PEMS equipment can be installed.

7 Outlook

There are several initiatives to monitor the emissions of vehicles on the road. For example, remote emission sensing initiatives has started across Europe. Very likely, high emissions are observed for a variety of vehicles in a variety of situations. This may trigger the In Sevice Conformity RDE testing by independent parties, as foreseen by the European Commission. However, high emissions, as shown above, may notbe reproduced in RDE tests. This requires, very likely, a different follow-up action by the type-approval authorities hinted at in RDE and Regulation (EU) 2018/858. Moreover, the cause and the mechanism of these occurances of high emissions should be understood from the monitoring studies, such that the results can be reproduced in additional testing, in multiple vehicles independently.

In summary, observed high vehicle emissions in normal use in monitoring programs are the start of an investigation, which may branch out in many directions. The In-Service Conformity RDE test is one of these directions, where specific test conditions may be needed. Tampering of vehicles is another avenue of investigation, as well as problems with poor maintenance. But the issues with elevated emissions, not covered by the RDE test protocol and the vehicles eligible for in-service confomity testing should remain in the picture. Moreover, the acceptable elevation levels and the test protocols should be investigated further.

The European Commission has asked the type-approval authorities to keep track of technology options to reduce emissions, to ensure the best available technology is applied. (Commission notice (2017) 352 final guidance document (26 Jan. 2017)).

With RDE3 legislation, the Granting Type-Approval Authority (GTAA) will approve the Auxiliary Emission Strategy (AES) declared by the manufacturer with information why an AES is needed to avoid engine damage. The underlying assessment will be based on a technical reasoning. For the stakeholders which are active in market surveillance or in-service conformity testing, access to these approvals would very much help for the evaluation of emission test results.

The extended documentation package is possibly commercially sensitive and may include elements of intellectual properties from a vehicle manufacturer. Hence, this assessment and the outcome is not generally available for other parties. Therefore, this information cannot be reviewed and compared with findings from, for example, monitoring programmes.

There still needs to be a framework in which elevated emissions found in the surveillance and monitoring programs are used to reassess AES evaluations. In principle an AES should prevent engine damage in exceptional situations which are not covered by RDE legislation. The (G)TAA evaluates the need of such AESs in the type approval process ahead of vehicle production. Once specific vehicle models enter the road it will be clear if these circumstances are truly exceptional, as conditions and driving behaviour can vary greatly over time and location. This information shared with independent testers can place test results in the right context. Therefore, a summary of the effects on emissions of the AESs present, without revealing commercially sensitive information, would improve the overall transparency. With such a summary, that should be part of publicly available documentation, complex discussions on test results of independent parties can be avoided.

As an alternative to an AES which intervenes with the emission control, OEMs could also consider an approach where the engine performance is (slightly) limited under exceptional conditions and driving behaviour.

8 Signature

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