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TNO report

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Assessment of risks for elevated NO_x emissions of diesel 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: Dutch Type Approval 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. If the effectiveness of emission control strategies would be focused on low emissions in normal use situations inside the RDE boundaries, elevated emissions due to different emission control strategies might occur in situations that are outside the scope of the RDE test conditions.

A focus on emission reductions under RDE conditions only, might 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 **Ministry of Infrastructure and the Environment** in the Netherlands has requested TNO to identify potential risks for elevated emissions in situations which are common 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 of NO_x, 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.

The overview of special situations with possibly elevated emissions 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 diesel-powered light-duty vehicles and NO_x emissions. Emissions from petrol-powered vehicles, in particular the particulates emissions from direct fuel injection engines, may be relevant as well but are outside the scope of this study.

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.

An inventory is given of possible technical reasons for the potentially elevated emissions in these cases. A technical reason for higher emissions 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.

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 NO_x emissions equivalent to the increase in CO_2 emissions could be considered acceptable. The correlation between NO_x and CO_2 emissions during the WLTC can be taken as reference for the application of such a factor.

Possible technical options to lower the NO_x 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.

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 NO_x reduction measures is not an isolated single change to a vehicle. There is a certain trade-off between low NO_x 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 NO_x reduction technologies. 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. 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.

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.

Deviating emission control strategies can potentially cause a significant increase in pollutant emissions. This is 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.

In many cases NO_x emission reduction is not trivial. There often is a certain trade-off between low NO_x emissions and other vehicle aspects. Therefore, efforts may be made to optimize the emission control strategy in order 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 the Environment in the Netherlands have requested TNO to identify possible situations, which are normal 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 NO_x 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.

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

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. 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.

Family on holiday

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.

German business driving

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.

Trailer or caravan towing

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.

Winter period

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 diesel-powered light-duty vehicles and NO_x emissions. Emissions from petrol-powered vehicles, in particular the particulates emissions from engines with direct fuel injection, may be relevant as well but are outside the scope of this study.

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 NO_x emissions, the intention of this document is not to propose new limits for the RDE legislation or to question RDE boundaries. RDE legislation covers the majority 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
After this introduction, the boundaries of the RDE test and vehicle conditions are described in chapter two. In chapter three the situations with possibly elevated emissions are identified. 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. Finally, in chapter 4, some general testing principles are drafted to detect these situations with possibly elevated emissions.

2 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 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, EMROAD and/or CLEAR, 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.

2.1 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 criterion.

<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[2]: 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.

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[3]	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 5 minutes.	-

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

Stops (speed < 1 km/h)	Several stops ≥ 10 s may be included. Total stoppage time shall be 6 - 30% of time of urban driving. If a stop lasts over 300 s, the emissions during 300 s following the stop shall be excluded from the evaluation.	-
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 1 shows $v * a_{pos}$ values for typical driving behaviour in the Netherlands, compared the RDE limit per road section.

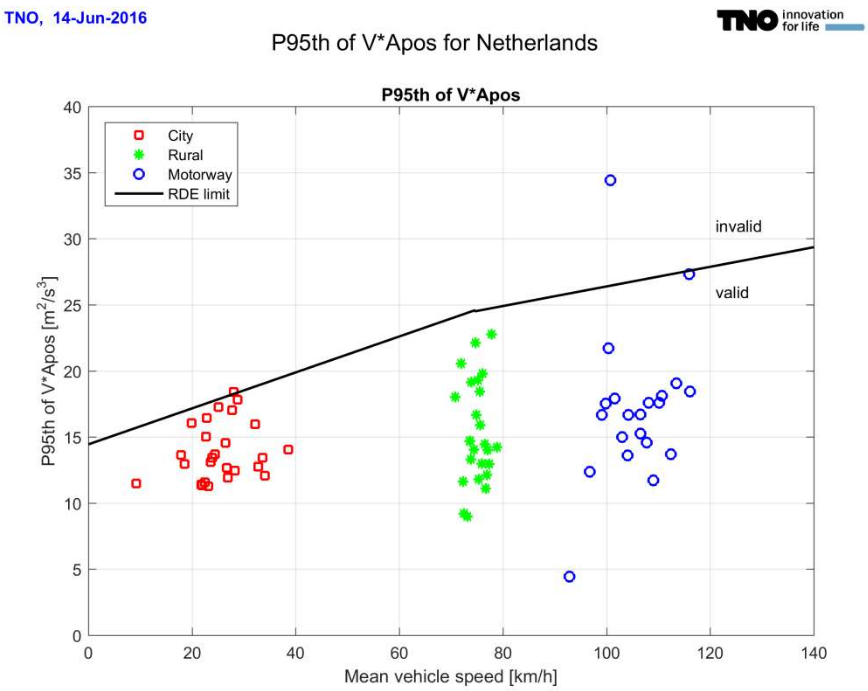

Figure 1: $v * a_{pos}$ values for typical driving behaviour in the Netherlands per road section [1]

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) $\bar{v}_k \le 74.6$ 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) $\bar{v}_k \le 94.05$ 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	$15 \text{ km/h} \le \bar{v}_{urban} \le 40 \text{ km/h}$	
Maximum speed	$v_{max} \le 145 \text{ km/h}$	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	

<u>Vehicle conditions</u>

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.

3 Possible situations with elevated emissions which are not covered by RDE legislation

In the previous chapter the most important boundary conditions for the execution of a valid RDE trip are described. The fact that there are boundary conditions automatically means that there are driving conditions which are not covered by the RDE test procedure. This is illustrated in Figure 2. 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.

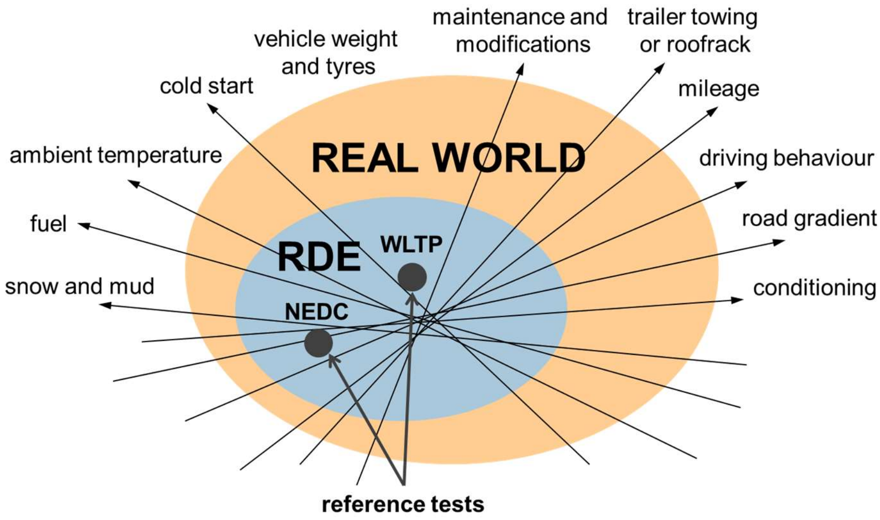

Figure 2: Illustration of how bandwidths of type approval testing, including RDE, do not cover all real-world conditions.

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 normal 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. The same applies for driving dynamics, altitude gain, and other aspects. Hence, eventually much 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 aforementioned 95% coverage of driving conditions implies another important complexity of RDE regulation. It means that it is accepted that elevated emissions occur in circumstances which only seldom occur in normal driving. This however does not mean that for translating RDE requirements to engineering targets these circumstances may be considered as situations for which no rules apply. A focus on emission reductions under RDE conditions only, might 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.*"

Instead, therefore, these exceptional circumstances should be considered as situations where for good reasons some leeway may be given. These exceptional circumstances and the reasons for elevated emissions can be put in perspective by applying limits on the accepted increase of emissions.

In this chapter, a range of situations with possibly elevated emissions is identified. This is to be considered a non-exhaustive overview. Thehe identified situations are listed, 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 RDE is not in place, this a is non-exhaustive overview;
- The expected impact on local air quality;
- An 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.

3.1 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. In order 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.

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, in particular

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.

3.2 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.

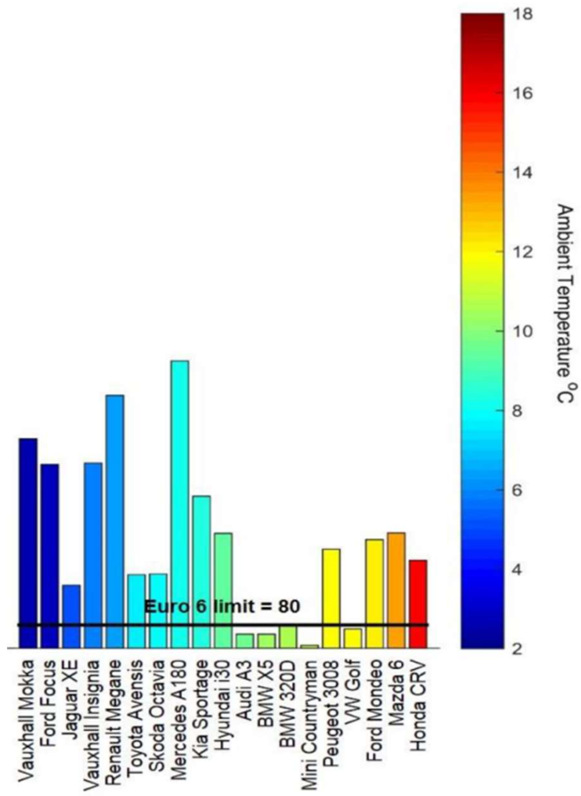

Figure 3: NO_x results from the recently published UK Vehicle Testing Programme.[4] Track test results plotted in order of increasing ambient temperature.

In particular, ambient temperatures can have a significant influence on NO_x emissions, as clearly indicated in Figure 3. 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

[4] 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 and road conditions with potentially elevated emissions

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:** 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[5] 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[6] **+** 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[7] 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

[5] As an extended use of the existing reduction factor of 1.6 for the extended conditions, see subsection 2.1.
[6] Water injection is still in development stage, with possible durability issues.
[7] 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.

3.3 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 4;
- 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.

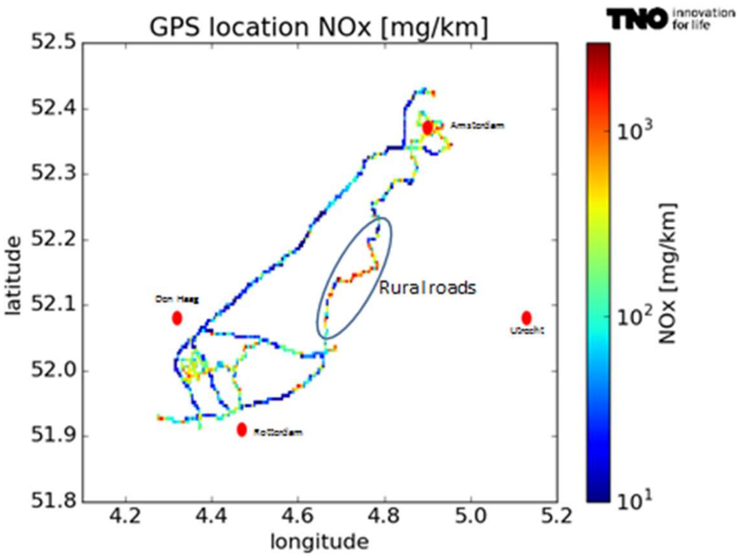

Figure 4: Emission measurement results of a modern Euro-6 diesel passenger car plotted on a real-world trip. The car showed good performance during driving on motorways with speed limits in force and expectedly higher emissions in urban areas. Emission performance during rural driving varied strongly. 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 related to the RDE trip composition

<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>> 15 sec idling after initial engine start</td><td rowspan="9">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.</td><td rowspan="9">High emissions on all road types</td><td rowspan="9">No significant increase compared to the RDE limits</td><td rowspan="9">Efforts to optimize the emission control strategy for all reasonable real-world conditions</td><td rowspan="9">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.</td></tr>
<tr><td>> 90 sec vehicle stop in cold start period</td></tr>
<tr><td>> 300 sec idling</td></tr>
<tr><td>Total trip > 120 minutes</td></tr>
<tr><td>Urban driving > 90 minutes</td></tr>
<tr><td>Alternative road section sequence</td></tr>
<tr><td>Motorway driving > 30 minutes</td></tr>
<tr><td>Alternative distance shares per road section</td></tr>
<tr><td>Manual engine switch off during trip</td></tr>
</table>

Total cumulative positive altitude gain > 1200 m per 100 km **Altitude: > 100 m difference between start/end**	Uphill driving: **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: cntrol strategies focused on reducing temperature **R:** Lower internal contamination **R:** Temperatures in engine and exhaust outside normal operation range **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	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[7]	Uphill driving: **+** 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 Downhill driving: **+** 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	**+** 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

3.4 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 5 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’. In particular for traction control and ESP, it is not clear from the RDE legislation if these specific modes are covered.

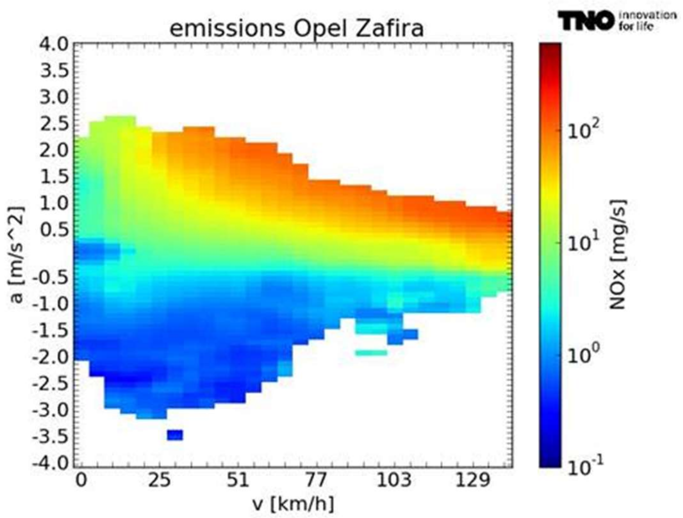

Figure 5: Typical emission map of a modern Euro 6 diesel passenger car, based on on-road emission measurements. Source: TNO 2016 R11177 “NO_x emissions of fifteen Euro 6 diesel cars: Results of the Dutch road vehicle emission testing program 2016”, Heijne et.al.

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

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

<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>v * a_{pos} [95] > RDE limit</td><td rowspan="2">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 all road types</td><td rowspan="2">At disproportionate high engine loads, when RDE limits are exceeded, a reduction factor based on the CO_2 emission rate may be applied[7]</td><td rowspan="2">+ 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 rowspan="5">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>Motorway driving at > 145 km/h</td><td>High emissions at high engine loads on the motorway</td></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></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>

3.5 Vehicle conditions

Based on the set specifications for vehicle conditions as described in the RDE legislation and in Regulation (EC) No 692/2008 (Reg. 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;
- 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 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[7] 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="3">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>
<tr><td>Vehicle not valid for ISC emission testing</td><td>High emissions on all road types</td><td>+ 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.</td><td>+ Efforts to optimize the emission control strategy for all reasonable real-world conditions

+ The application of catalysts with an enhanced durability</td><td>Drive a regular RDE trip with a vehicle that has:
+ Driven > 100.000 km
+ An expired maintenance interval
+ Some OBD errors</td></tr>
</table>

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

4 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.

4.1 Risk based testing within the boundary conditions

Risk based testing is meant to recognize the situations where elevated emissions may or are expected to 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 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.

4.2 '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 be 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;
- 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 ˚Cor 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.

4.3 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 kinds 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.

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, and requires an operator 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. As an example, depending on the situation, it can be sufficient to measure only NO_x and CO_2 for diesel engines.

Compared to PEMS testing, monitoring can be rather 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.

5 Signature

Apeldoorn, 3 July 2017

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