Expectations for Actual Euro 6 Vehicle Emissions

Based upon Ricardo experience, public domain data and dedicated measurements

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Concawe
Environmental Science for European Refining

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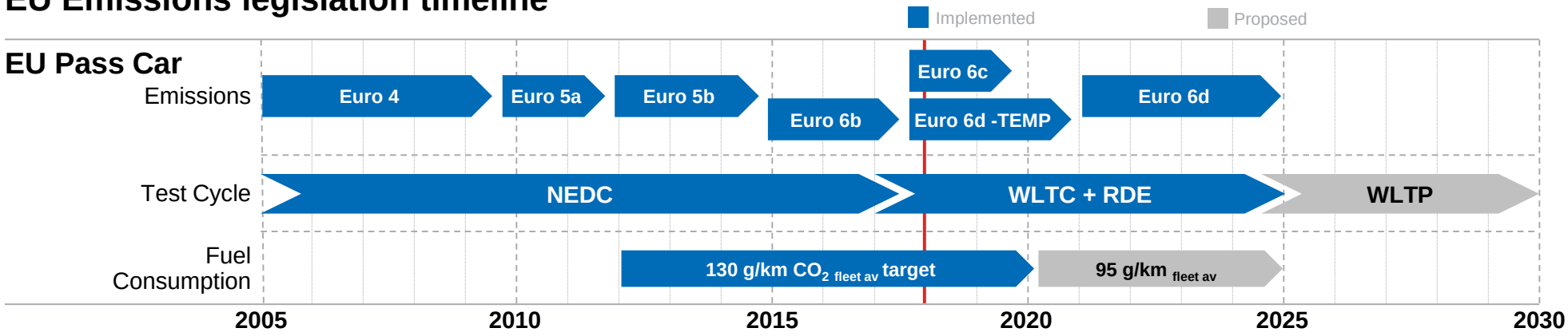
Successive levels of Euro 6 legislation are aimed at reducing the difference between legislated and real world emissions

Executive Summary (1/5)

- Successive levels of Euro 6 legislation, culminating in Euro 6d, are introducing new emissions testing requirements aimed at reducing the difference between legislated and real world emissions
  - Light duty vehicles were initially certified at Euro 6 emissions limits using the NEDC test cycle which evaluates emissions control over a relatively narrow operating range
  - Euro 6d vehicles are required to be certified using the WLTC and RDE, controlling emissions over a wide, real-world driving operating range
  - The need for a more representative test methodology was established by both the European Commission and key stakeholders many years ago
    - However, the complexities associated with developing viable test procedures and measurement protocols required over 5 years of work to gain approval

EU Emissions legislation timeline



This study aims to outline the expectation of actual Euro 6 vehicle emissions under real world driving conditions

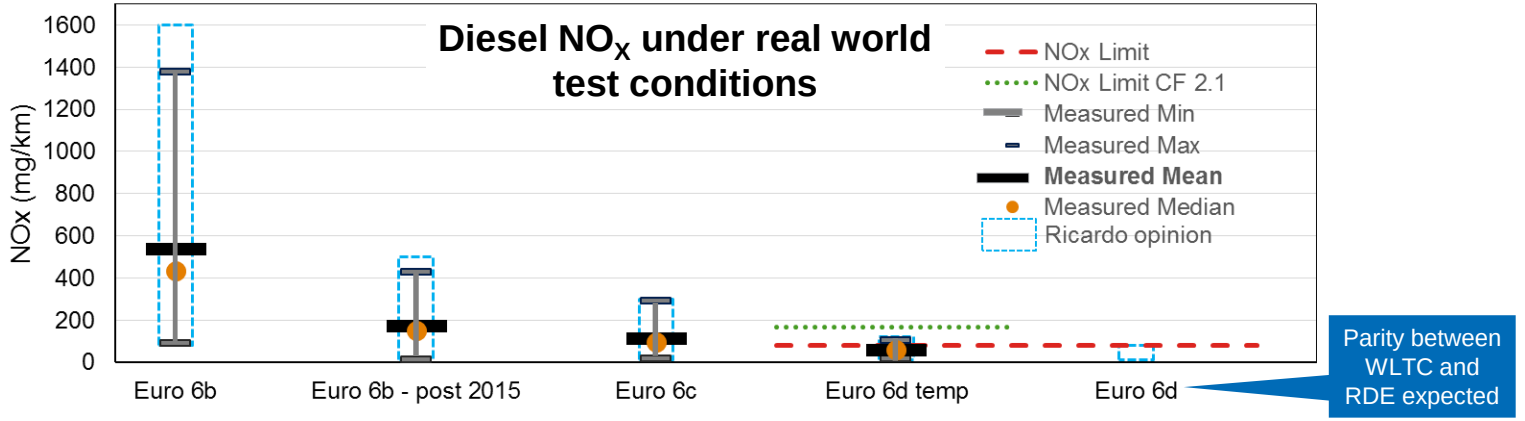
Executive Summary (2/5)

- To outline the expectation of actual Euro 6 vehicle emissions, this study summarises actual tailpipe emissions data from Euro 6 vehicles under real world driving conditions from Ricardo and other public domain sources
  - The study focuses on emissions from diesel passenger cars but also includes data from gasoline passenger cars and Euro VI heavy duty vehicles
- To be valid, the RDE trip must meet distance, trip composition and average speed requirements as well as dynamic boundary conditions
  - Ricardo real world data are tested under robustly validated conditions compliant with so-called moderate RDE temperature and altitude conditions, which are designed to cover the majority of European driving conditions
  - The results do not include severe or extended RDE cycles
  - Other public domain sources include a number of representative real driving tests on road which do not strictly fit within the RDE cycle limits

Evidence suggests that the technical solutions applied to LD diesels will achieve a substantial reduction in real world driving emissions

Executive Summary (3/5)

Key findings from light duty diesel Euro 6 vehicle emissions data



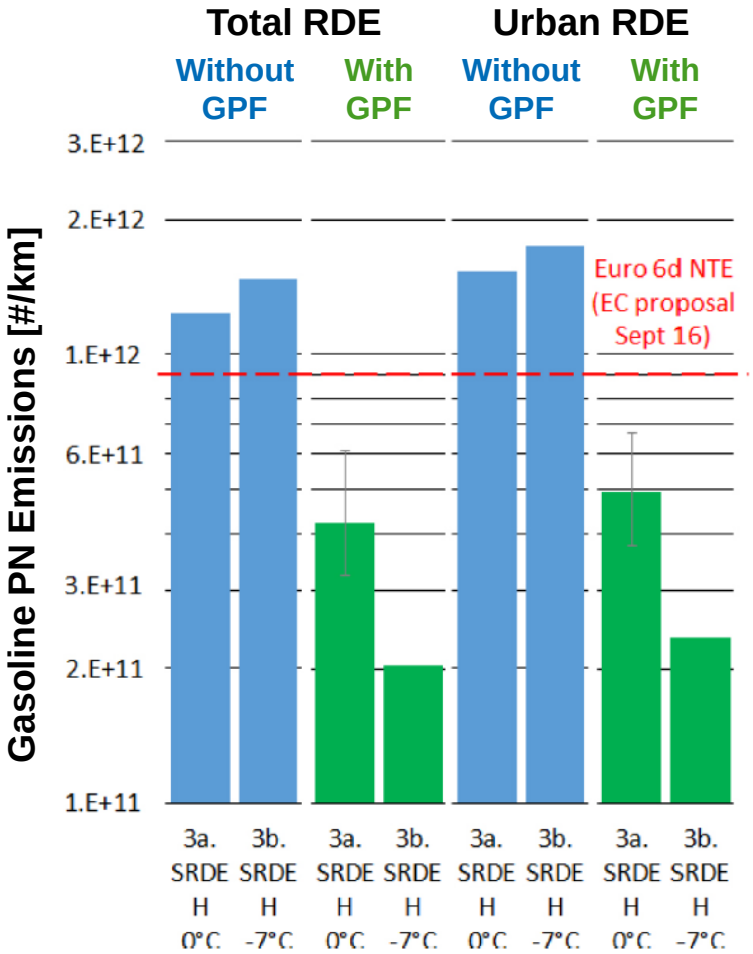
- Although there are only a limited number of Euro 6d-temp ready vehicles to date, the evidence suggests that the technical solutions applied will achieve a substantial reduction in RDE emissions
  - The results show real world emissions are substantially reduced by successive levels of Euro 6 legislation, from Euro 6b to Euro 6d
  - The evidence suggests that the technical solutions applied to Euro 6d will achieve regulated conformity factors under real world driving at moderate RDE temperature and altitude conditions, which are designed to cover the majority of European driving conditions
  - Emissions limits may still be exceeded by driving conditions outside of RDE specifications
- Real world Particle Number (PN) data for Euro 6c and 6d vehicles are also within the Euro 6 limits

On Gasoline vehicles, fitment of a Gasoline Particulate Filter will be required in many cases to meet Euro 6d PN emissions requirements

Executive Summary (4/5)

Key findings from light duty gasoline Euro 6 vehicle emissions data

- Achieving NO_X limits appears to be significantly less of a challenge for gasoline vehicles than with diesel
- Evidence suggests that the technical solutions applied to Euro 6c and 6d-temp can achieve regulated conformity factors during real world driving
- Real world PN data suggests that fitment of a GPF means that gasoline vehicles will be capable of meeting Euro 6d emissions requirements on all RDE cycles



Published heavy duty NOx data meets in-service conformity NOx limits, except under unladen congested traffic conditions

Executive Summary (5/5)

Key findings from heavy duty diesel Euro VI vehicle emissions data

- Published heavy duty NO_X data show that vehicles mostly meet real world NO_X limits
- In some cases, under unladen congested traffic conditions, the SCR aftertreatment is not able to maintain an effective temperature for NO_X conversion
  - Ricardo experience is that specific configuration and calibration of the emissions control systems is required for diesel NO_X control
- PM and PN for heavy duty vehicles under real world conditions are well within Euro 6 limits

***Ricardo Expert Insight**:*
NO_X emissions of Heavy Duty (HD) diesel vehicles are low and are reducing, mostly due to SCR aftertreatment systems. SCR NO_X conversion efficiency is high when engines operate at high load. HD engines operate under high load for the majority of the HD duty cycle; therefore NO_X is kept at a minimum.

Contents

This report considers actual passenger car and heavy duty emissions under Euro 6 and Euro VI legislation, focussing on diesel NOx

Report Objectives

- To summarise the steps in Euro 6 legislation
- To show the expected actual tailpipe emissions under Euro 6, focusing on NOx emissions from diesel passenger cars
- To provide a narrative showing visual progression of how actual gasoline and diesel passenger car emissions are expected to develop under Euro 6 legislation
- To provide a summary of public domain on-road heavy duty Euro VI emissions information

Vehicles

- The following vehicle categories are considered
  - Light duty internal combustion engine vehicles (Class M)
  - Heavy duty vehicles (Class N)

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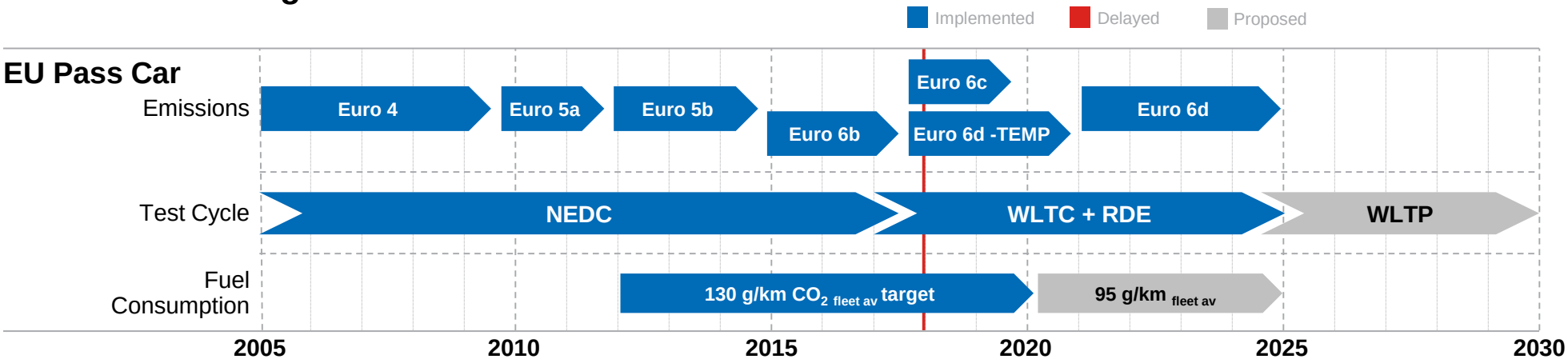
Euro 6 legislation for the type approval of passenger cars is aimed at reducing the difference between legislated and real world emissions

EU Emissions Legislation Timeline



The aim of Euro 6 is to tighten the emissions limits from Euro 5. Euro 6 is being introduced in stages

- **Euro 6b** was applied to new type approvals for passenger cars from September 2014, and applied to all light duty vehicles from September 2016 – tests were based on the NEDC
- **Euro 6c,** currently being phased in, introduces WLTC and will apply to new vehicles from September 2018
  - The introduction of the WLTC as an inter-continental standard for LD test procedures had been in consultation, Europe has led its implementation through its use in Euro 6c
- **Euro 6d-TEMP** introduces the use of Real Driving Emissions (RDE) testing, with a temporary NO_X conformity factor (CF) of 2.1. Euro 6d-TEMP applied from September 2017 for new type approvals, and will apply from September 2019 for all new M and N1 Class I vehicles Temporary CF for PN is still to be determined, 1.5 CF is proposed
- **Euro 6d** has full Euro 6 emission requirements, and RDE testing against final conformity factors (NO_X CF equivalent to 1.5). Euro 6d applies to new type approvals from January 2020, and all vehicles from January 2022. Temporary CF for PN is still to be determined

Source: EMLEG; Commission Regulation (EU) 2016/646 of 20 April 2016; Ricardo analysis

The addition of the procedures around RDE and the progressive reduction in NO_X CFs result in more stringent emissions targets

- There has been some concern that tests have consistently shown a marked difference between legislated emissions levels and those measured under real driving conditions
  - In particular, NOx emissions from light duty diesel engines tend to be higher under real driving conditions than when measured during the type approval process
- Successive levels of Euro 6 legislation, culminating in Euro 6d, are introducing new emissions testing requirements aimed at reducing the difference between legislated emissions levels and real world levels
  - In May 2015 the EU Commission's Technical Committee of Motor Vehicles (TCMV), voted to accept the new Real Driving Emissions (RDE) test procedure. The limits will be applied in two stages and stipulate the maximum ratio between the legislated emissions limit under laboratory testing and those measured in real driving conditions, this is expressed with a "conformity factor" (CF)
  - In June 2016 the TCMV, voted in favour of the World Harmonised Light Vehicle Test Procedure (WLTP) for new passenger cars and light commercial vehicles. This first phase of introduction of the WLTP is the implementation of the emissions test based on the Worldwide Light-duty Test Cycles (WLTC)

Implementation Dates for M-class Vehicles

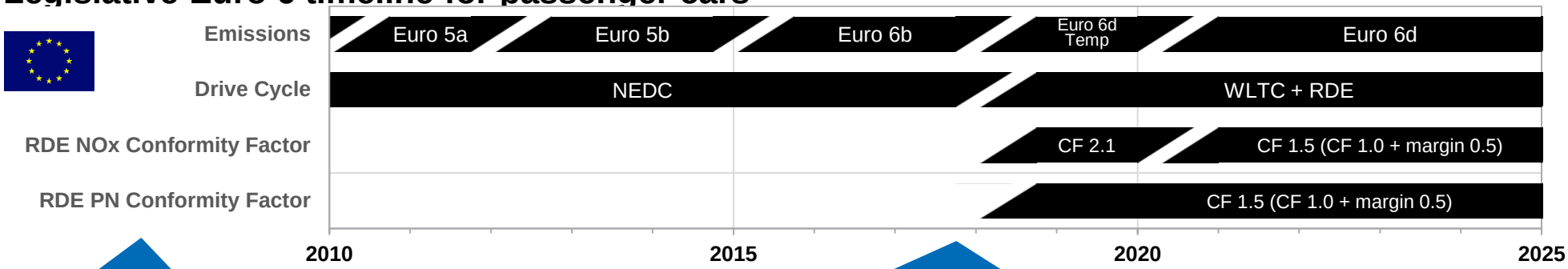
Emission Standard	Homologation Method	OBD Standard	Real Driving Emissions	2015	2016	2017	2018	2019	2020	2021
EU6b	NEDC	6-1	Voluntary Monitoring							
EU6b	NEDC	6-1	Voluntary Monitoring							
EU6c	WLTC	6-2	Voluntary Monitoring							
EU6c	WLTC	6-2	Voluntary Monitoring							
EU6d-temp	WLTC	6-2	Temporary CF = 2.1							
EU6d-temp	WLTC	6-2	Temporary CF = 2.1							
EU6d	WLTC	6-2	Final CF ≤1.5							
EU6d	WLTC	6-2	Final CF ≤1.5							

Key: Type Approval | New Vehicles

Source: Ricardo EMLEG Emissions Legislation Database (1) http://www.emleg.com

Euro 6d passenger car emissions limits are tested on both the WLTC and RDE with a conformity factor of 1.5 for NOx and PN

Legislative Euro 6 timeline for passenger cars



$$CF = \frac{RDE\ Test\ Result(g/km)}{Legislated\ Limit\ (g/km)}$$

Euro 6c overlaps with 6d
Euro 6c requires monitoring of RDE emissions only

Euro 6 Emissions Limits[1,3,4]			
Emissions		**Gasoline (Positive Ignition)**	**Diesel (Compression Ignition)**
Oxides of Nitrogen	NO_x (mg/km)*	60	80
Particulate Mass	PM (mg/km)	4.5[A]	4.5
Particle Number	PN (#/km)	6×10^{11}	6×10^{11}
Hydrocarbons + NOx	HC + NOx (mg/km)	-	170
Carbon Monoxide	CO (mg/km)	1000	500
Total Hydrocarbons	THC (mg/km)	100	-
Non-Methane Hydrocarbons	NMHC (mg/km)	68	-

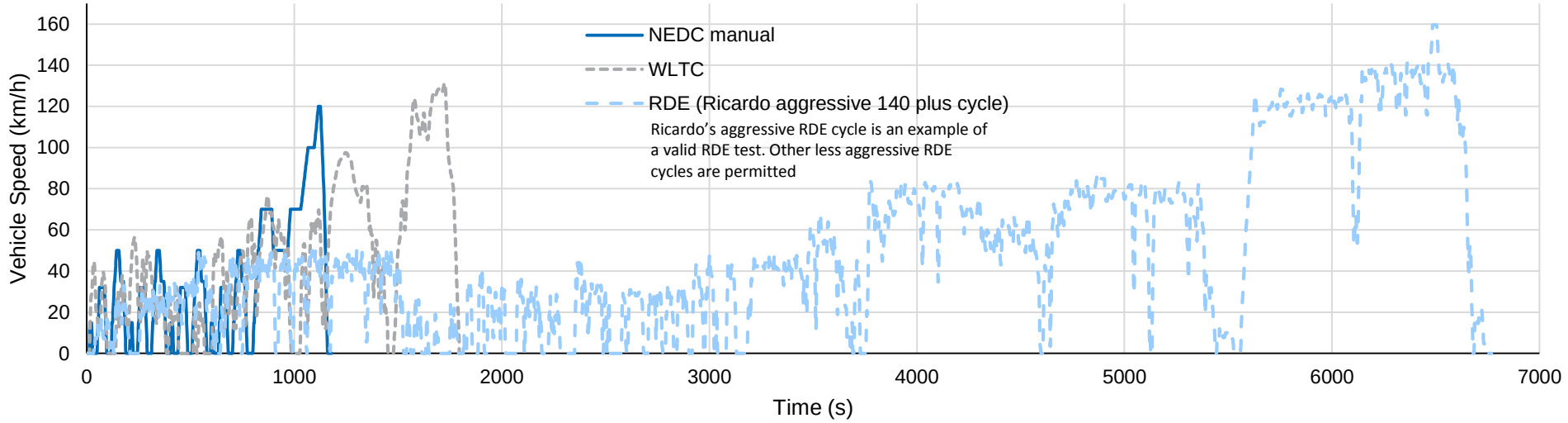
PN measurements are for non-volatile particles with d50 (50% percent counting efficiency for particles) at ~23nm

* NO_X is the regulated pollutant and is the quantification of both NO and NO_2. Tailpipe NO_2 is a respiratory irritant and is of primary concern in cities

Source: Ricardo EMLEG (1), WLTC (2), EU Parliament (3,4)…… [A] Direct injection only(17)

NEDC, WLTC & a representative, aggressive RDE trip show top speed and acceleration demands are increased for Euro 6d compliance

Drive cycles used for Euro 6 passenger cars



Drive Cycle	Duration (s)	Average Speed (km/h)	Maximum Speed (km/h)	Maximum Acceleration (m/s^2)
NEDC	1180	33.3	120.0	1.04
WLTC	1800	46.5	131.3	1.67
RDE (Aggressive)	6769	49.7	159.6	4.17

Ricardo's aggressive RDE cycle is an example of a valid RDE test. Other less aggressive RDE cycles are permitted

- RDE and WLTC have
  - Both an increased number and magnitude of accelerations
  - Higher maximum speeds
  - Reduced cold start influence compared to NEDC

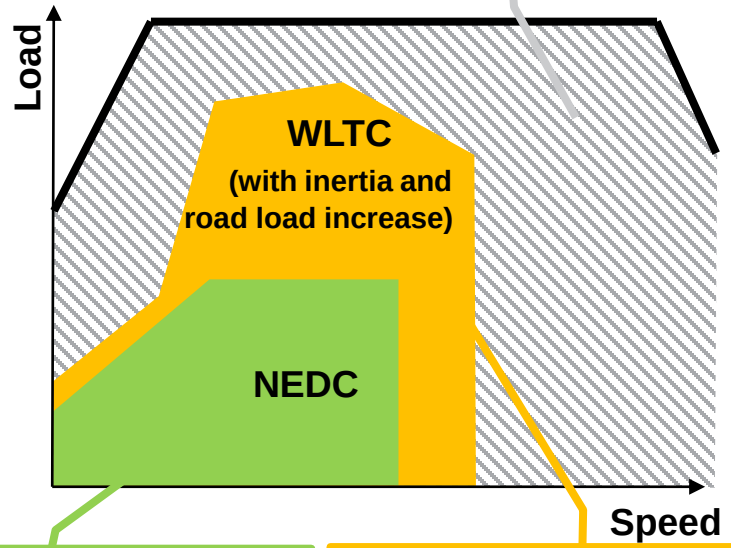
  These are more typical of European urban and highway driving styles than the NEDC
- RDE acceleration rates may be in excess of four times that of the NEDC
- The range within RDE compliant driving is representative of normal driving, including gradients

Source: EU Regulation, Ricardo

The implementation of WLTC and RDE from 2017 will extend the engine speed and load conditions at which emissions are regulated

- Euro 6d-temp and Euro 6d legislation requires emissions to be compliant under RDE conditions
  - RDE has the potential to cover a significant part of speed load operating window including full load at a range of ambient and altitude conditions
- The main challenge with RDE is to develop diesel NOx control systems which are effective under a wide range of engine operating points and hence a range of exhaust temperatures
  - The NOx aftertreatment technologies (EGR, LNT and SCR) are most effective over different exhaust temperature ranges (see Appendix 1)
- The conditions which present a particular challenge for NOx control systems are:
  - Urban driving conditions when SCR aftertreatment technologies may not reach an efficient operating temperature
  - High load conditions when exhaust temperatures may be too high for LNT aftertreatment technologies to be effective
  - Low temperatures which may limit the use of EGR, in order to protect some engine components from damage

- **Real Driving Emissions (RDE)** will be measured on-road using Portable Emissions Measurement System (PEMS), in real road and traffic conditions
- RDE has the potential to cover a significant part of the speed load operating window including full load at a range of ambient and altitude conditions



The **New Engine Drive Cycle (NEDC)** focuses on light load and low speed engine conditions

The **Worldwide harmonised Light vehicles Test Cycle (WLTC)** will require emissions control over wider speed load range.

Euro 6d NOx control is therefore likely to require a careful mix of different aftertreatment technologies

Contents

Real world emissions data is presented from a number of sources for NOx, Particle Number (PN) and Particulate Matter Mass (PM)

RDE Data

- The data presented was from a range of public domain articles and papers together with Ricardo test data
  - The majority of the public domain data is for Euro 6b vehicles with a few Euro 6c vehicles
  - The Ricardo data is for pre-Euro 6c and research Euro 6d-temp
- The data set for late Euro 6 certified diesel vehicles was limited
  - At the time of the study there were no Euro 6d temp or final certified vehicles. One “Euro 6d temp ready” vehicle (Mercedes E220d; certified as Euro 6c) was tested by Ricardo
  - Further Euro 6d temp data was included from Ricardo research
- Further information on the data sources is provided in Appendix 2

All Ricardo real world data presented is from valid RDE cycles. Other real world data includes valid RDE and other driving cycles

Presented test data

Click link:

NOx – Diesel

NOx – Gasoline

PN – Diesel

PN – Gasoline

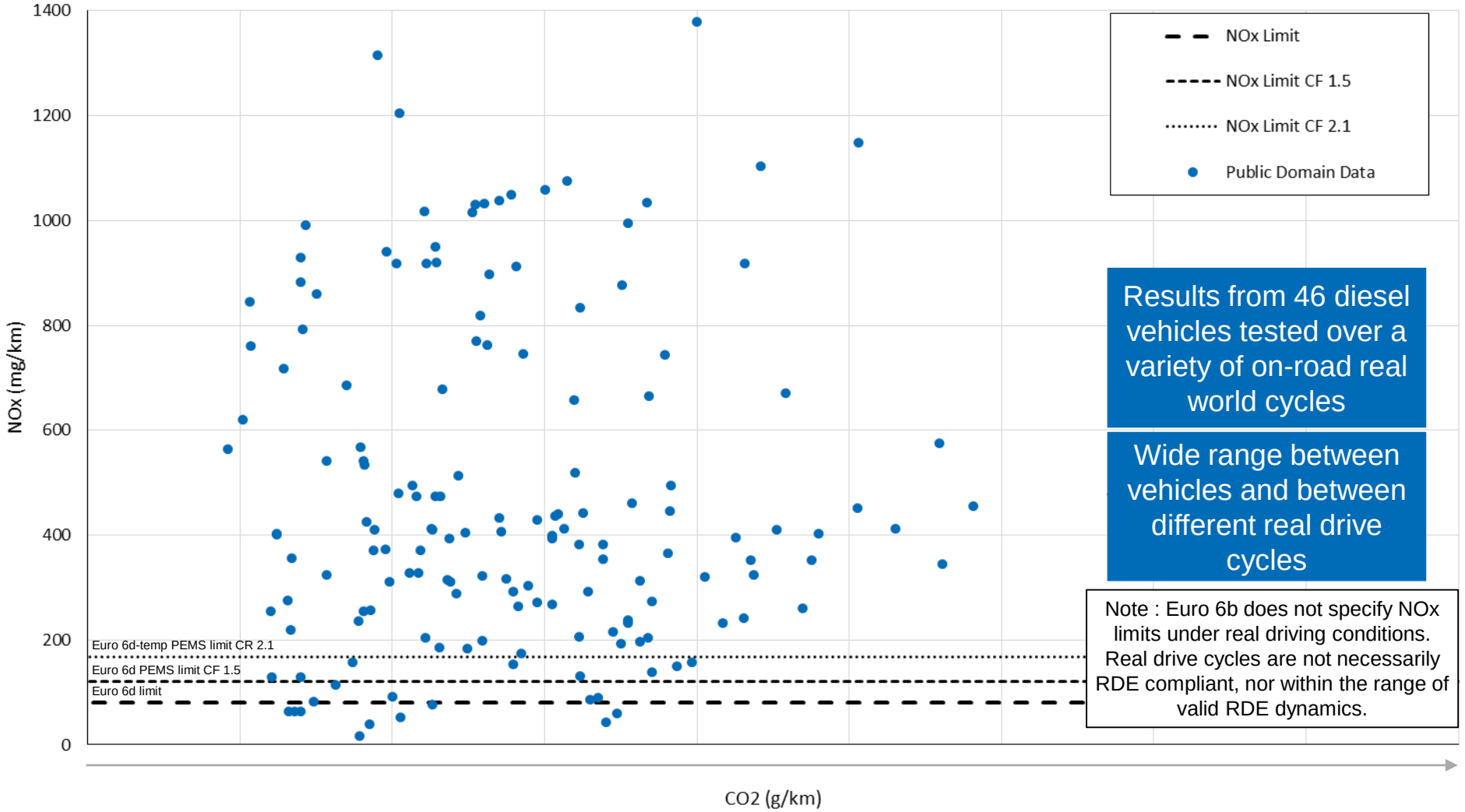
PM – Diesel

RDE cycles and measurement

- The RDE emissions test data is presented against the test CO_2 results, the higher the CO_2 value the more aggressive the RDE cycle or generally the larger the vehicle
- All Ricardo RDE tests are valid RDE cycles compliant with Euro 6d
  - The 'envelopes' representing the spread of the RDE data have a wide CO_2 range, which indicates a range of different RDE cycles, and a range of different vehicle types were tested
  - Results do not include severe or extended RDE cycles
- The other RDE data presented includes both valid RDE cycles, other real driving and other real world driving cycles (such as London specific cycles)
  - This includes a number of representative real driving tests on road which do not strictly fit within the RDE cycle limits (see Appendix 1 for details of cycle limits)
- Portable Emissions Measurement (PEMS) equipment is used to measure the emissions of NOx and PN
  - For diesel vehicles, if PN can be met then PM can be easily achieved, therefore there is no requirement for RDE PM measurements
  - PM is difficult to measure using PEMS, so it is typically measured using a chassis dynamometer which runs a replication of an RDE compliant cycle

Euro 6b emissions measured on road show a wide range of NOx emission levels dependent upon vehicle and on real drive cycle

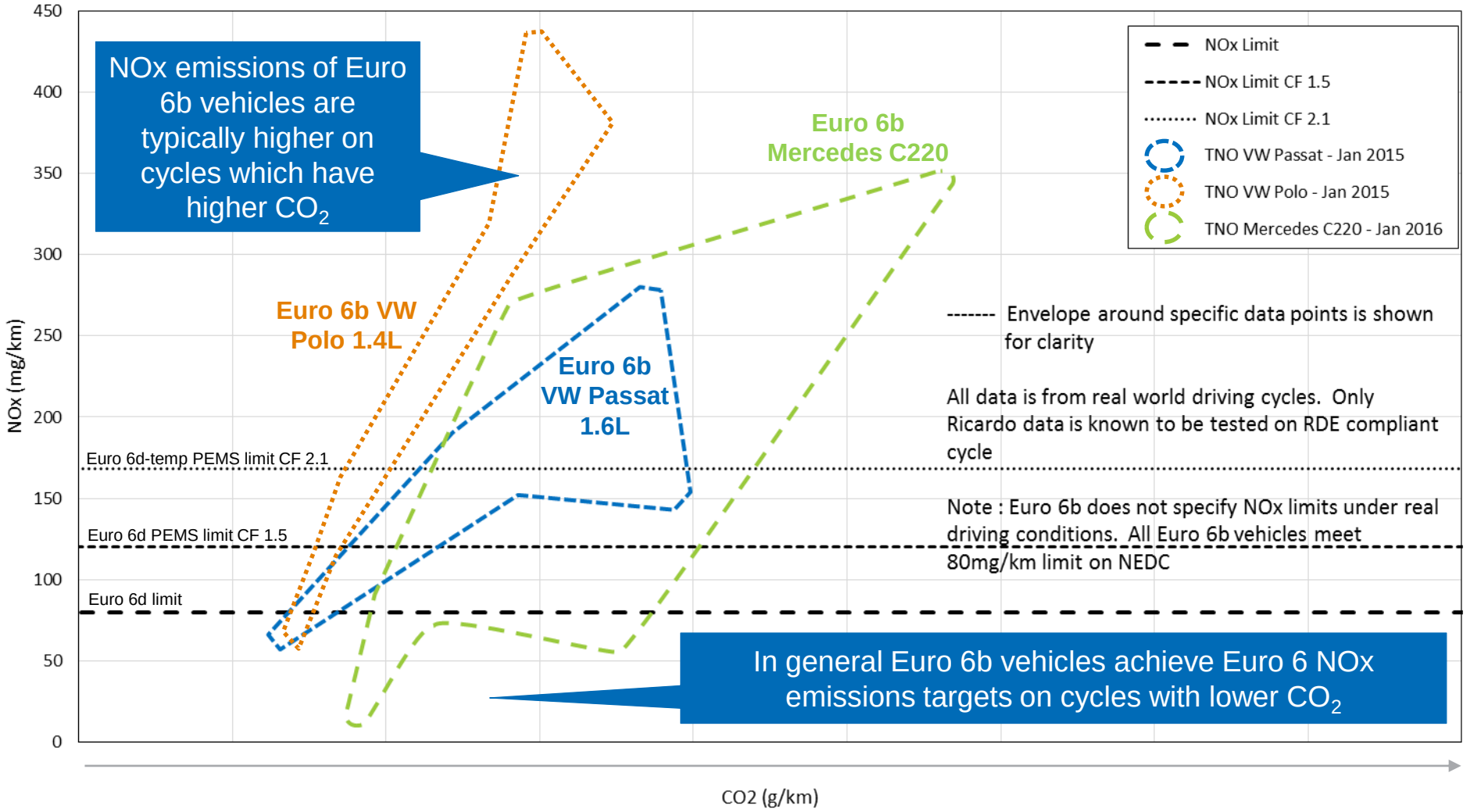
Diesel NOx – Euro 6 – On road driving emissions



Source: References published in 2016 and 2017 as listed in Appendix 2. Note: Specific Euro 6 level is not given in references but is likely to be Euro 6b.

More recent Euro 6b vehicles meet Euro 6 NOx levels under some real world driving cycles but exceed under other cycles

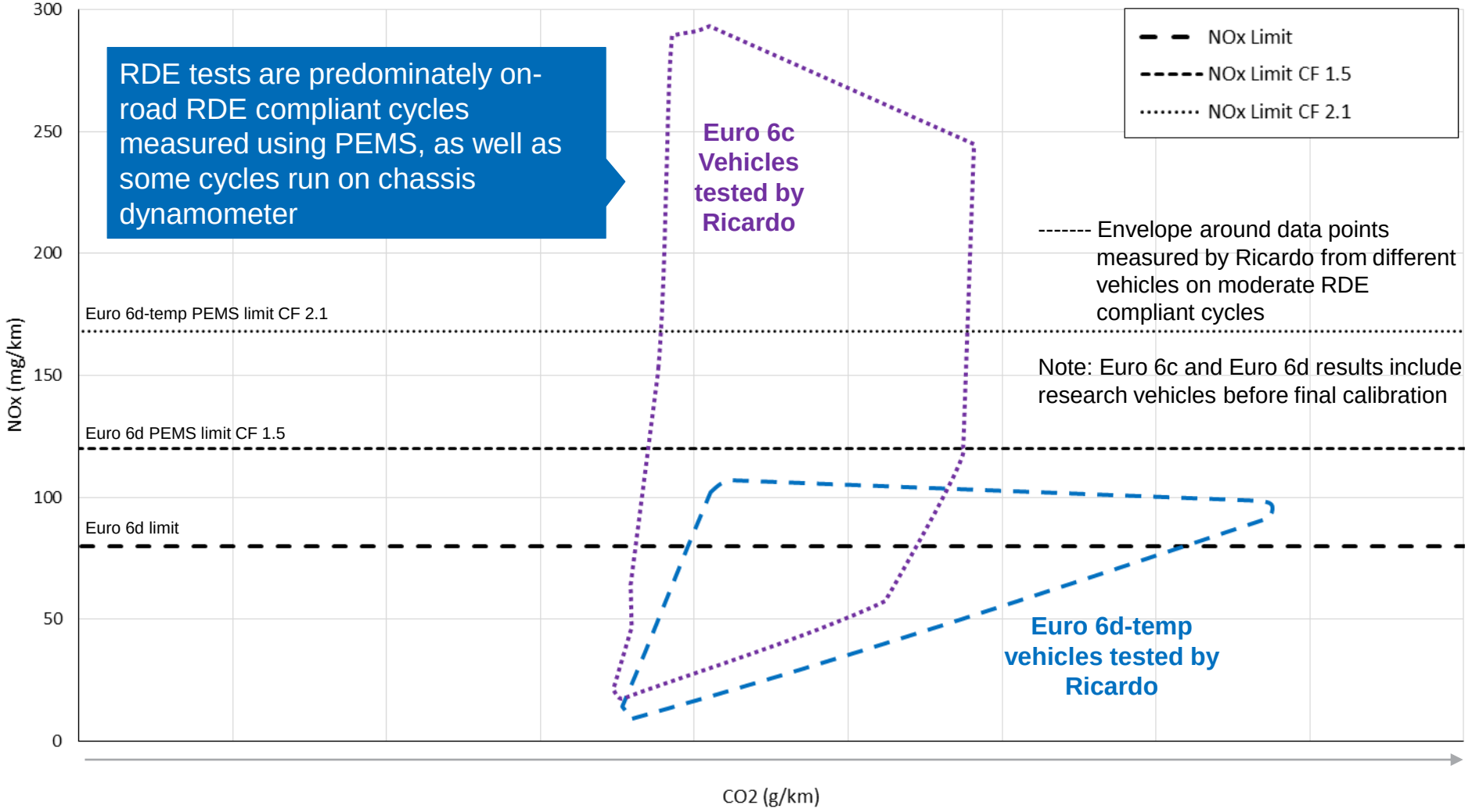
Diesel NOx – Euro 6b vehicles which meet Euro 6 NOx levels under at least 1 real world cycle



Note: References published in 2016 and 2017 as listed in Appendix 2

Some Euro 6c vehicles meet Euro 6 NOx levels during real world driving cycles while other vehicles exceed on some cycles

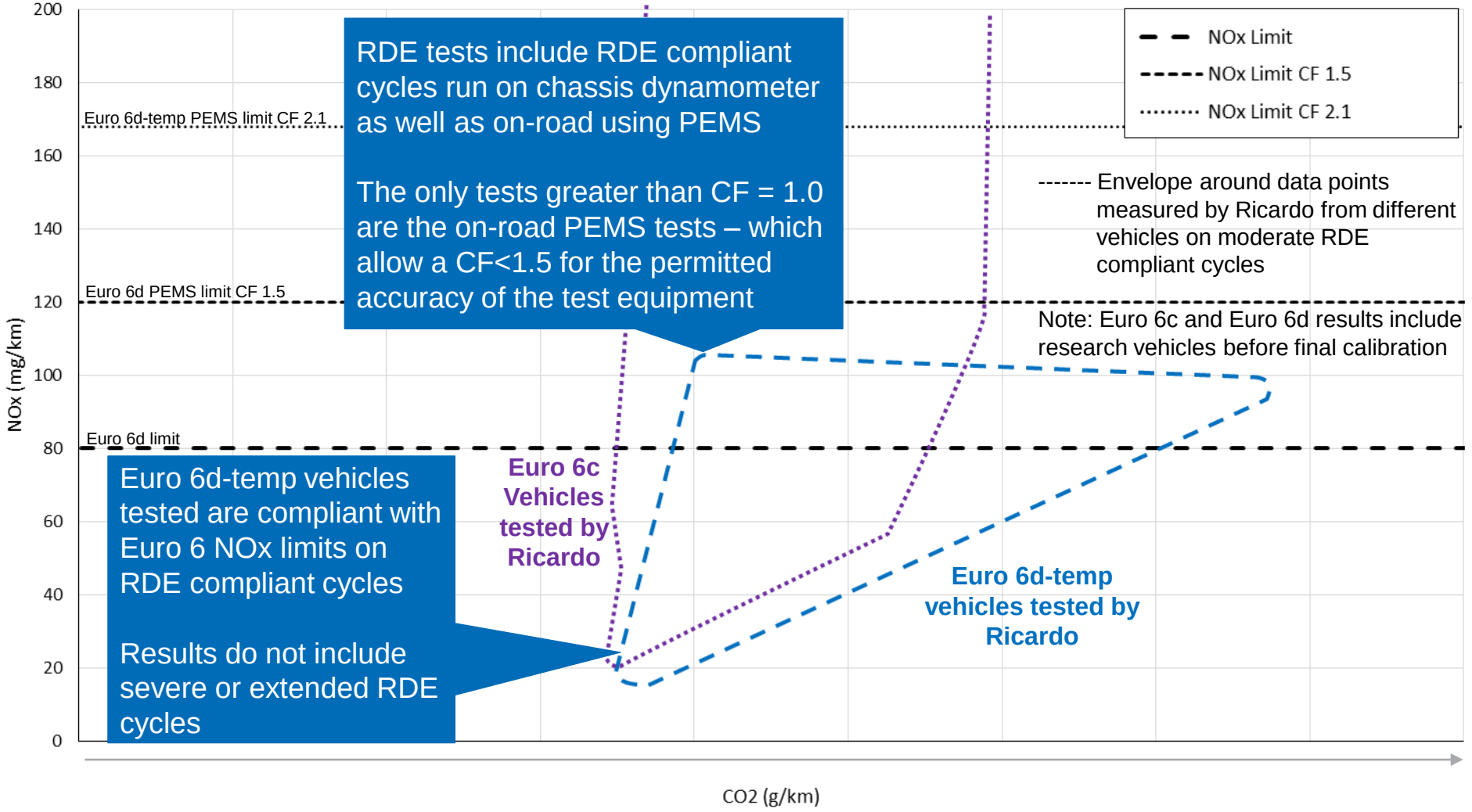
Diesel NOx – Euro 6c and Euro 6d-temp vehicles on RDE cycles



Note: Specific data points are not shown due to contractual confidentiality

Future Euro 6d-temp vehicles can satisfy Euro 6 NOx limits over a range of moderate RDE compliant cycles

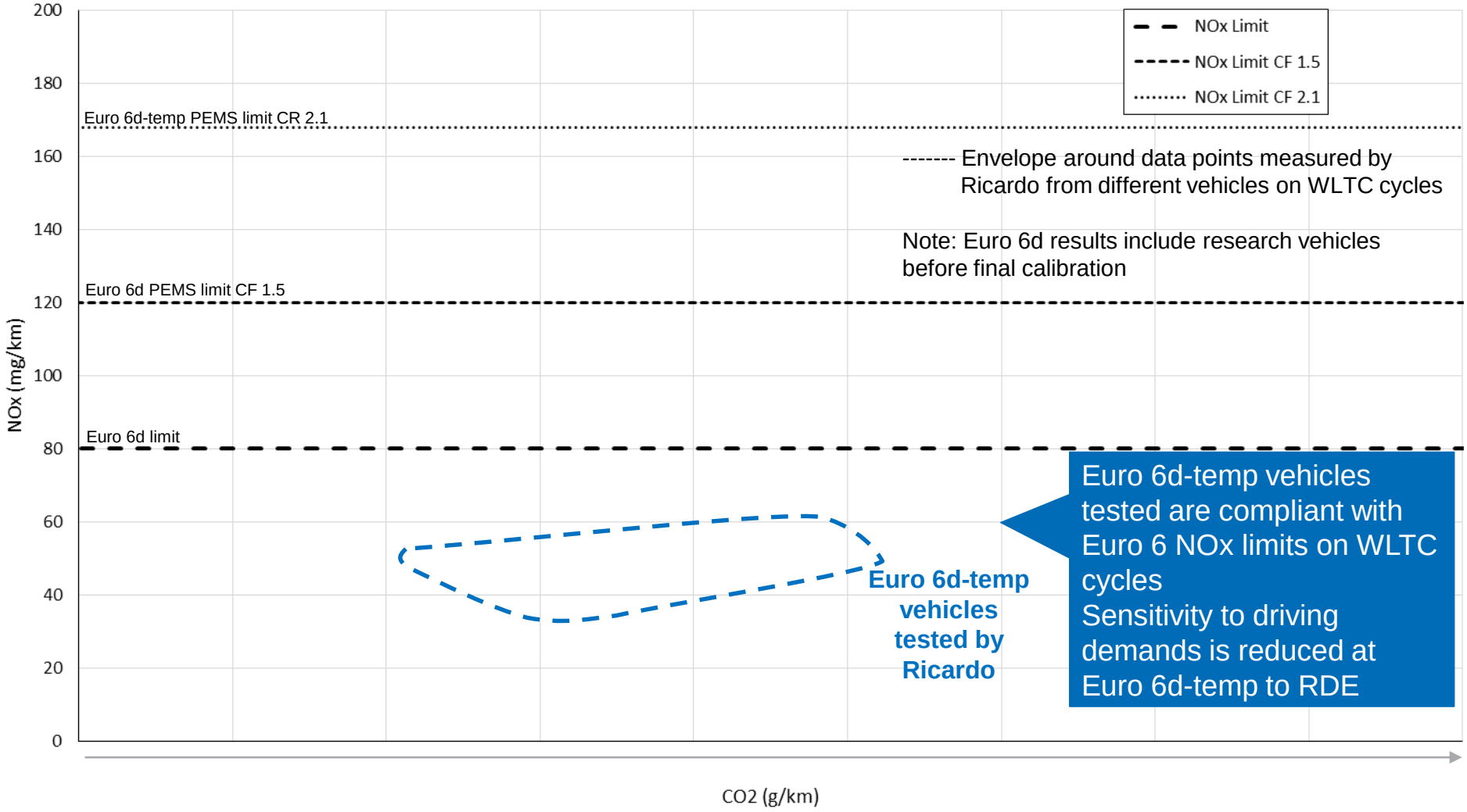
Diesel NOx – Euro 6c and Euro 6d-temp vehicles on RDE cycles



Note: Specific data points are not shown due to contractual confidentiality

Development and early certification Euro 6d-temp vehicles shown to comfortably satisfy Euro 6 NOx limits over WLTC cycles

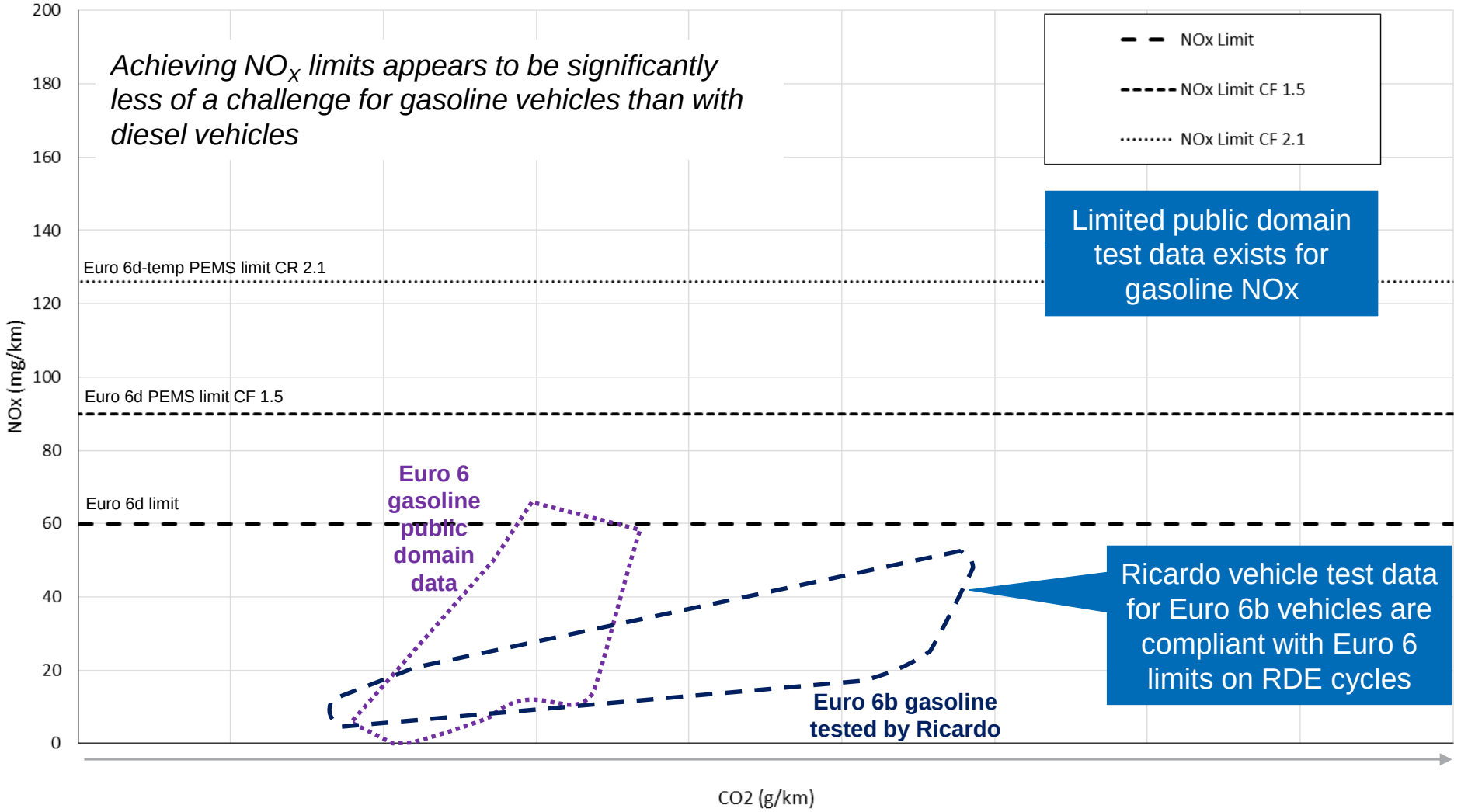
Diesel NOx – Euro 6d-temp vehicles on WLTC cycles



Note: Specific data points are not shown due to contractual confidentiality

Gasoline NOx data available on RDE cycles are within Euro 6 conformity factor limits

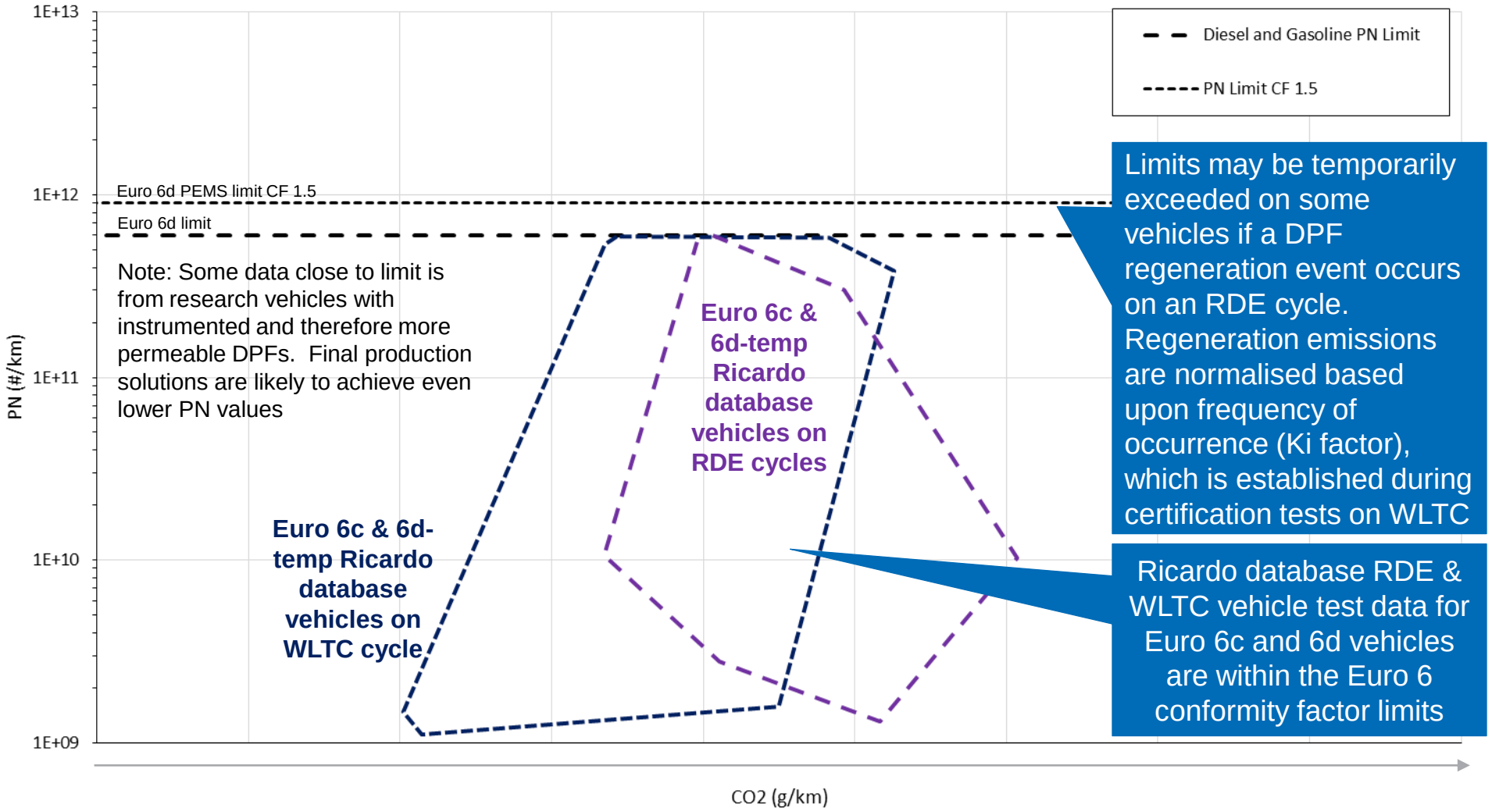
Gasoline NOx – Euro 6 (all stages) RDE vehicle tests



Note: Specific Ricardo data points are not shown due to contractual confidentiality

All available diesel PN data is within Euro 6 limits for RDE cycles

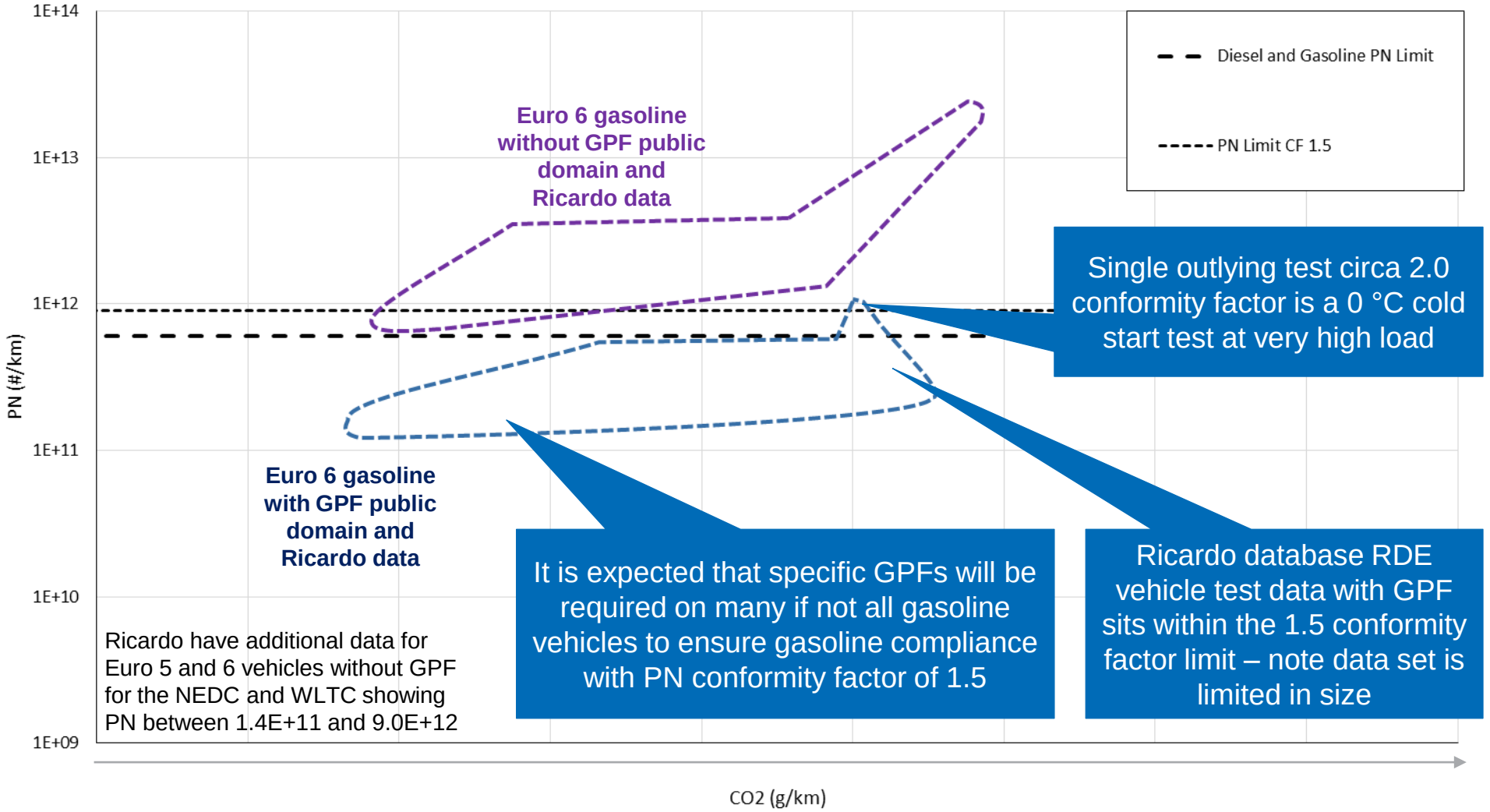
Diesel PN – Euro 6 (6c and 6d) RDE and WLTC vehicle tests



Note: Specific Ricardo data points are not shown due to contractual confidentiality.

Gasoline PN can be within Euro 6d limits during RDE with a Gasoline Particulate Filter (GPF) fitted

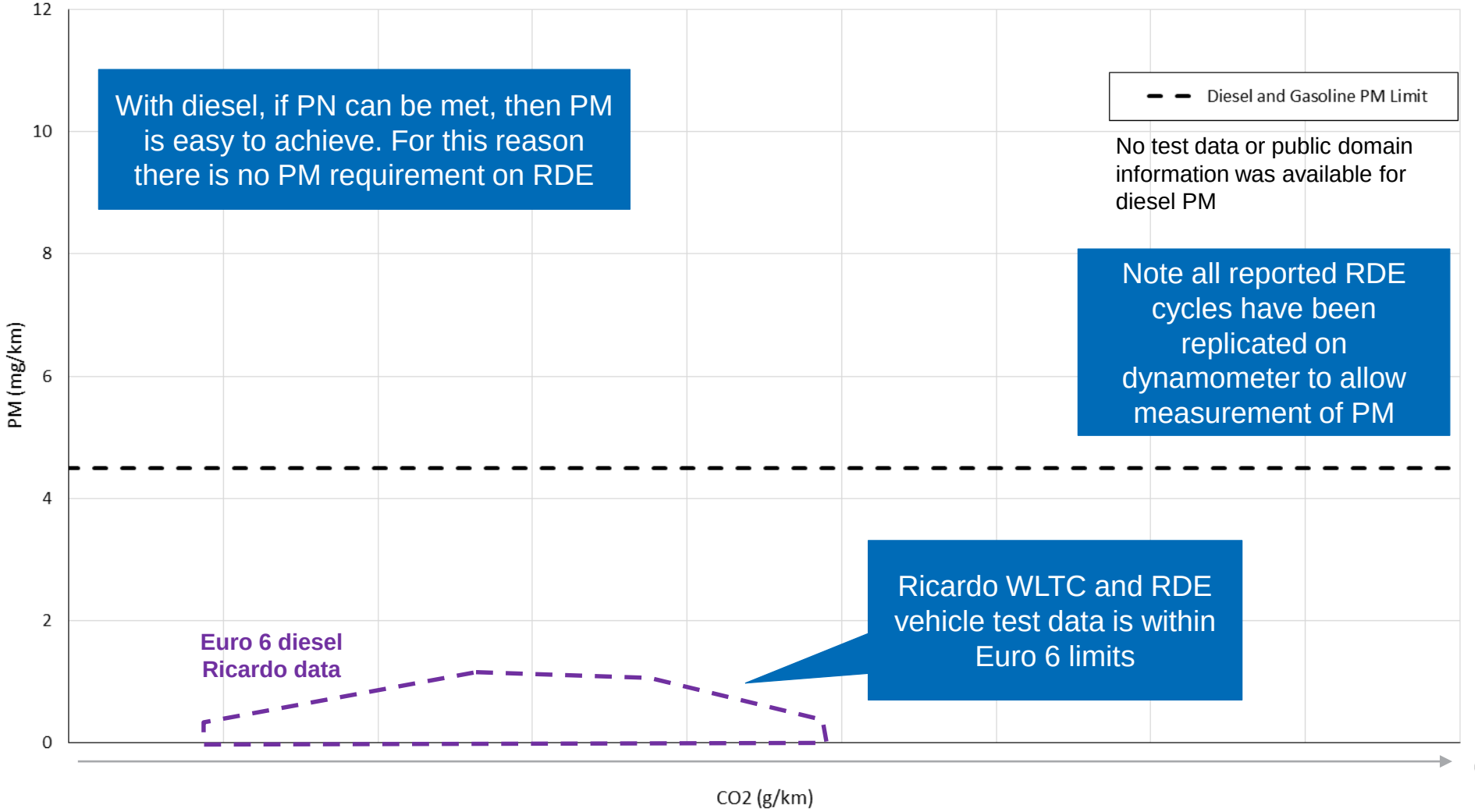
Gasoline PN – Euro 6b RDE vehicle tests



Note: Specific Ricardo data points are not shown due to contractual confidentiality

Available diesel PM on WLTC and RDE is within Euro 6d limits

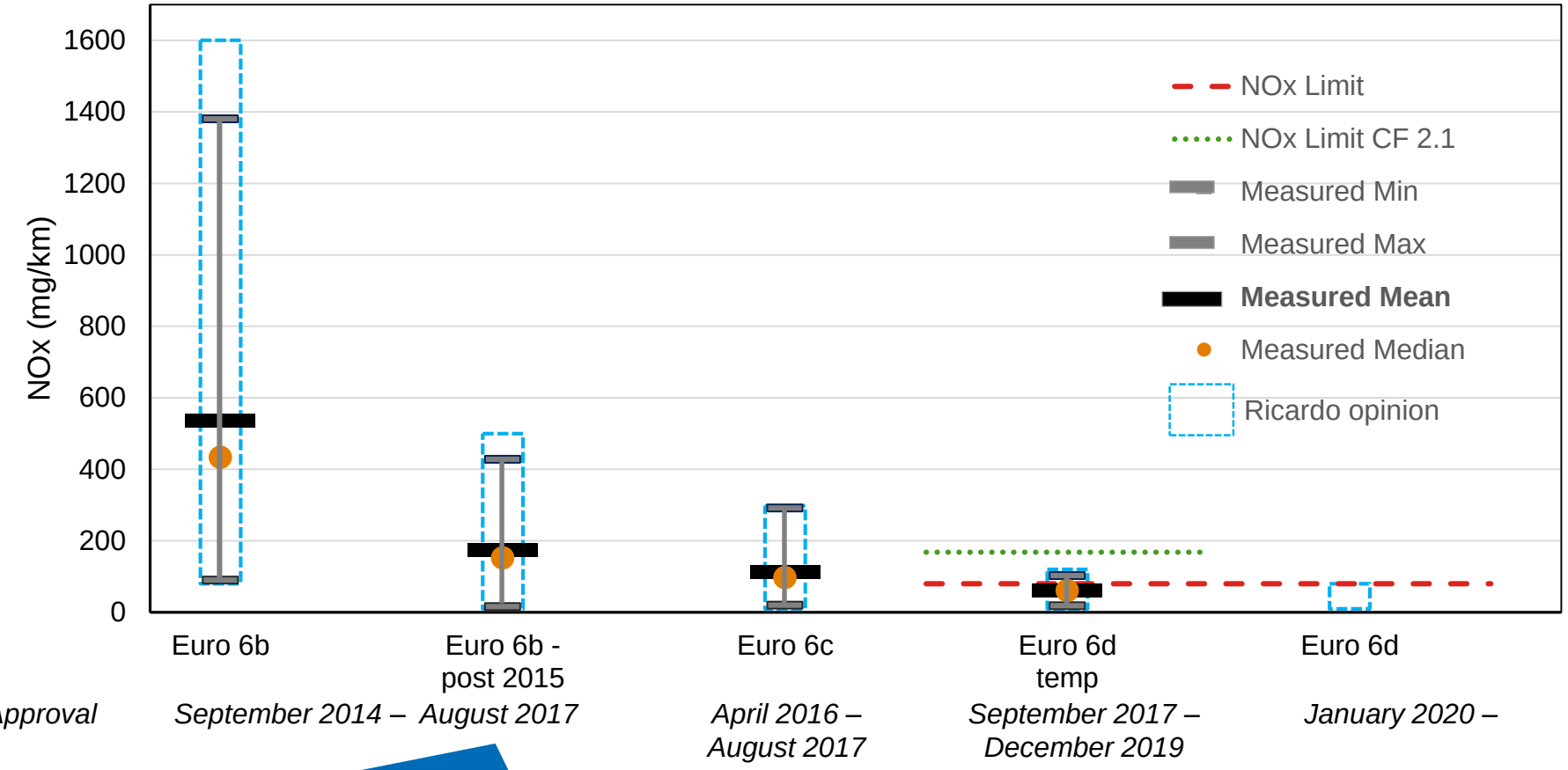
Diesel PM – Euro 6 (all stages) WLTC and RDE vehicle tests



Note: Specific Ricardo data points are not shown due to contractual confidentiality

The stages of Euro 6 introduction show a progressive reduction in real world driving diesel NOx emissions

Diesel NOx under real world test conditions



Selected Euro 6b vehicles post 2015 meet Euro 6 NOx levels under at least one real driving test cycle with a smaller emissions band as indicated

Measured values are the range of emissions from the studies presented in this report together with Ricardo test data.
Ricardo opinion estimates a representative range of emissions from certified vehicles during on road RDE testing
Ricardo opinion values relate to whole RDE cycles, not part RDE cycles (i.e. urban)

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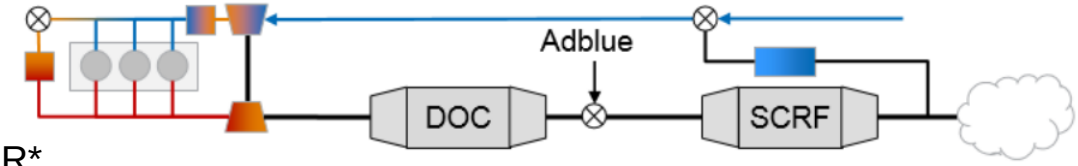
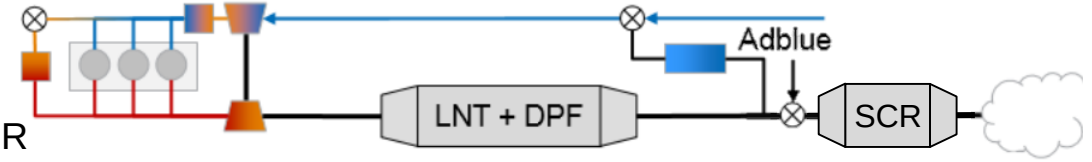
Euro 6d NOx control requires a mix of solutions including high and low pressure EGR, DPF, SCR and LNT or additional SCRs

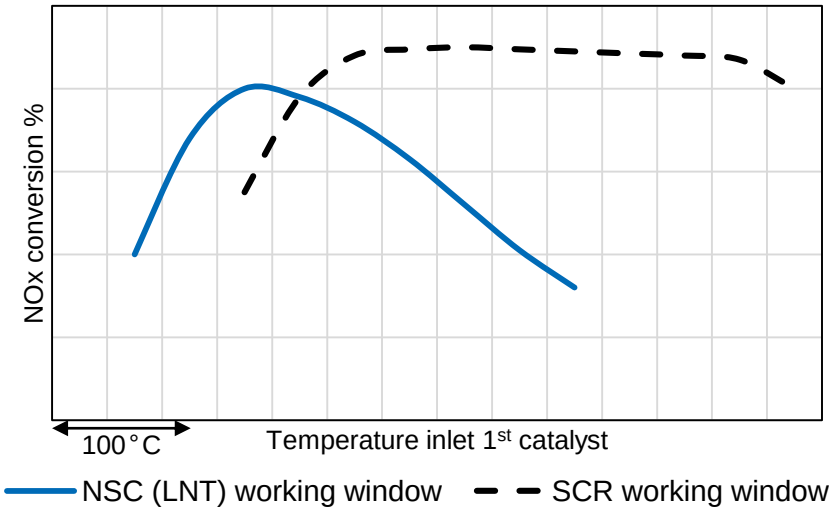
Diesel NOx control technology options



- The expected requirements for RDE are:
  - EGR (both HP & LP expected) + DOC + SCR*
    - Risk of insufficient NOx conversion efficiency at low load and low temperature such as in an urban environment



  - EGR (both HP & LP expected) + LNT* + SCR
    - Further benefits are seen from combining an LNT with SCR to provide good NOx conversion efficiency throughout the operating temperature range
    - Therefore compliance is possible throughout the full range of RDE cycles including low temperature urban and high temperature highway
  - The DOC and SCRF system featured in the VW Passat 2.0L (Euro 6c certified) which shows compliance for the RDE cycle tested within Euro 6d final conformity factors**



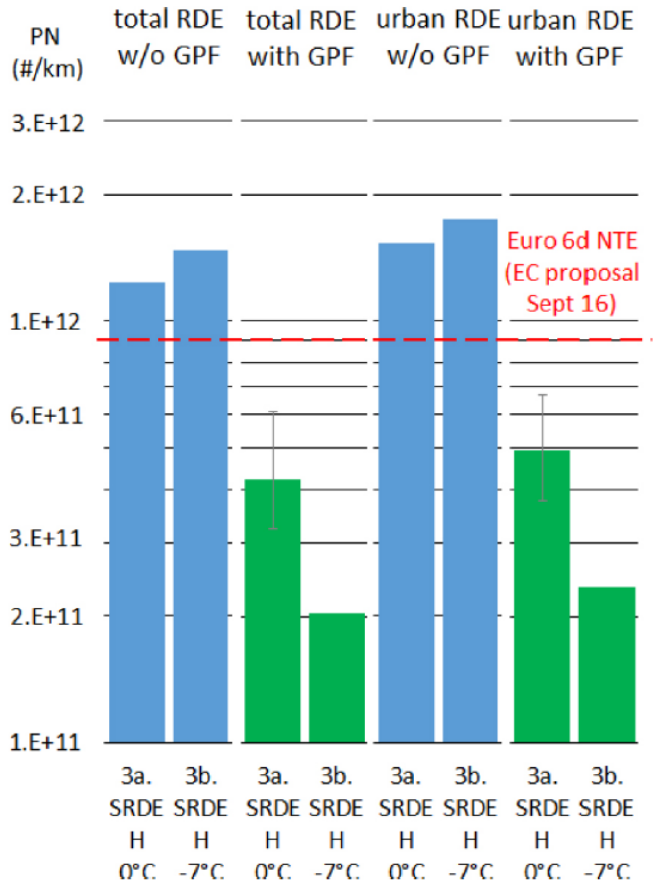
Source: Ricardo analysis; Hipp, et al (16)

*aftertreatment also includes DPF for PM and PN control, **a range of RDE cycles tested, but these do not cover every possibility

Euro 6d gasoline PN conformity across a wide range of RDE cycles has been shown to be possible with fitment of a specific GPF

Gasoline PN control requirements for Euro 6d final

- Work on a production B-Class GDI vehicle showed full compliance with gaseous emissions requirements for Euro 6d-final RDE, including in extended RDE conditions. Particle number results were higher than planned limits.
  - However, research shows that fitment of a Gasoline Particulate Filter (GPF) can solve the PN problem, moving PN emissions within limits for a range of RDE cycles and WLTC[14]
  - The worse case for PN on the vehicle tested (1.5 litre, B-Class) is a severe RDE cycle at low temperatures, and even this can be brought within limits, including within a conformity factor of 1.0[14], see graph right
- The data presented suggests that fitment of a GPF means that gasoline vehicles will be capable of meeting Euro 6d emissions requirements on all RDE cycles



Source: Ricardo analysis, AECC (14)

Careful catalyst system specification & calibration is critical for Diesel NOx control and for Euro 6d-final real world driving compliance

Expected actual emissions for Euro 6d final

- Evidence to date of this study, although from a limited number of certified vehicles, suggests that the technical solutions applied to Euro 6c and 6d-temp can achieve regulated conformity factors during real world driving
  - These solutions enable a significant reduction of diesel NOx from the range seen in production at Euro 6b
  - Specific configuration and calibration of the emissions control systems is required for diesel NOx control
    - For example using significant EGR across the speed and load range
    - Ensuring SCR operating temperature permits high NOx conversion efficiency
- GPF technology will be required for the majority of gasoline vehicles to ensure compliance with Euro 6d RDE

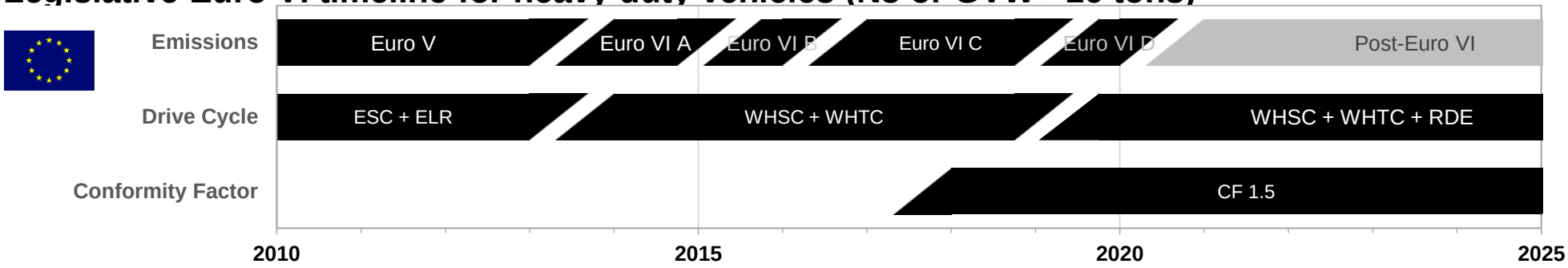
Expectations of Actual Euro 6 Emissions Limits					
Emissions		**Gasoline**	**Technical Solution**	**Diesel**	**Technical Solution**
Oxides of Nitrogen	NO_x (mg/km)	✓	TWC	✓	DOC + EGR + SCR and / or LNT* and / or SCRF
Particulate Mass	PM (mg/km)	✓	GPF – new	✓	DPF/CDPF + DOC or DOC + SCRF
Particle Number	PN (#/km)	✓	GPF – new	✓	DPF/CDPF or SCRF
Ammonia	NH3 (ppm)	-	-	✓	ASC for use with SCR
Carbon Monoxide	CO (mg/km)	✓	TWC	✓	DOC
Total Hydrocarbons	THC (mg/km)	✓	TWC	✓	DOC
Non-Methane Hydrocarbons	NMHC (mg/km)	✓	TWC	✓	DOC
⁺Diesel - multiple NOx catalyst may be required to cover a broad NOx control window, leading to multiple different potential solutions					

Note: "✓" indicates current technical solutions, "✓" indicates technical solution recently introduced or in development

Contents

Euro VI heavy duty vehicles are required to be compliant with both engine and vehicle emissions tests

Legislative Euro VI timeline for heavy duty vehicles (N3 or GVW >16 tons)



Euro VI Emissions Limits – Diesel					
Emissions		Engine Testing			Vehicle Testing
		Steady state (WHSC)	Transient (WHTC)	Not to Exceed	Conformity Factor
Oxides of Nitrogen	NO_x (mg/kWh)	400	460	600	1.50
Particulate Mass	PM (mg/kWh)	10	10	16	-
Particle Number	PN (#/kWh)	8.0×10^{11}	6.0×10^{11}	-	-
Ammonia	NH_3 (ppm)	10	10	-	
Carbon Monoxide	CO (mg/kWh)	1500	4000	2000	1.50
Total Hydrocarbons	THC (mg/kWh)	130	160	220	1.50
Non-Methane Hydrocarbons	NMHC (mg/kWh)	-	-	-	-

Vehicle PEMS testing is for in-service conformity. OBD emissions thresholds are being phased-in in four stages. Stages A and B are the phase-in stages for the NO_X OBD threshold, whilst stages C and D apply the general requirement threshold.

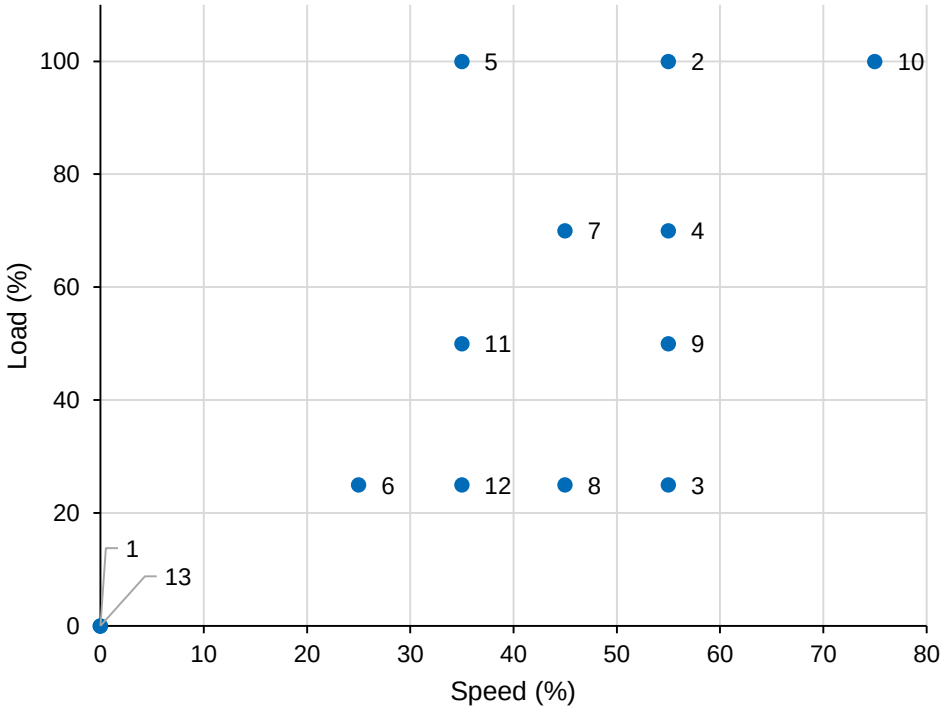
Euro VI	NOx (mg/kWh)
A and B	1,500
C and D	1,200

Source: Ricardo EMLEG (1), EU, Annex XV (7), EU Legislation (8)

Both steady state and transient engine testing covers the majority of the engine speed-torque map, including operation at high loads

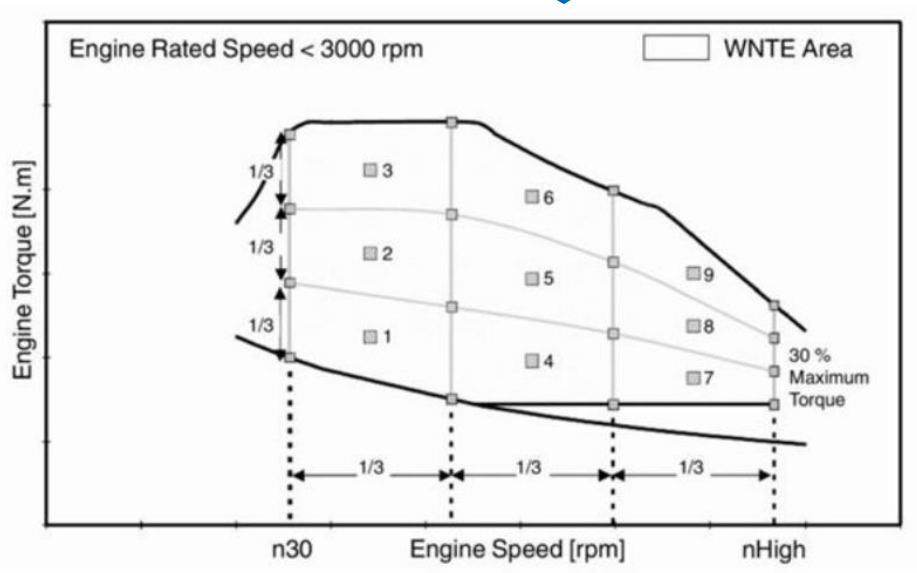
Engine testing cycles for Heavy Duty Euro VI – Steady State (WHSC)

- WHSC testing is engine and aftertreatment only testing on an engine dynamometer of 13 operating points which cover a wide range of load and speed operation
- Not To Exceed (NTE) zones are extensions of the 13 operating points, which force good emissions control in the areas where emissions are challenging to reduce



Emissions limits must be met at 13 operating points

Not to Exceed limits apply to the majority of the engine operating map

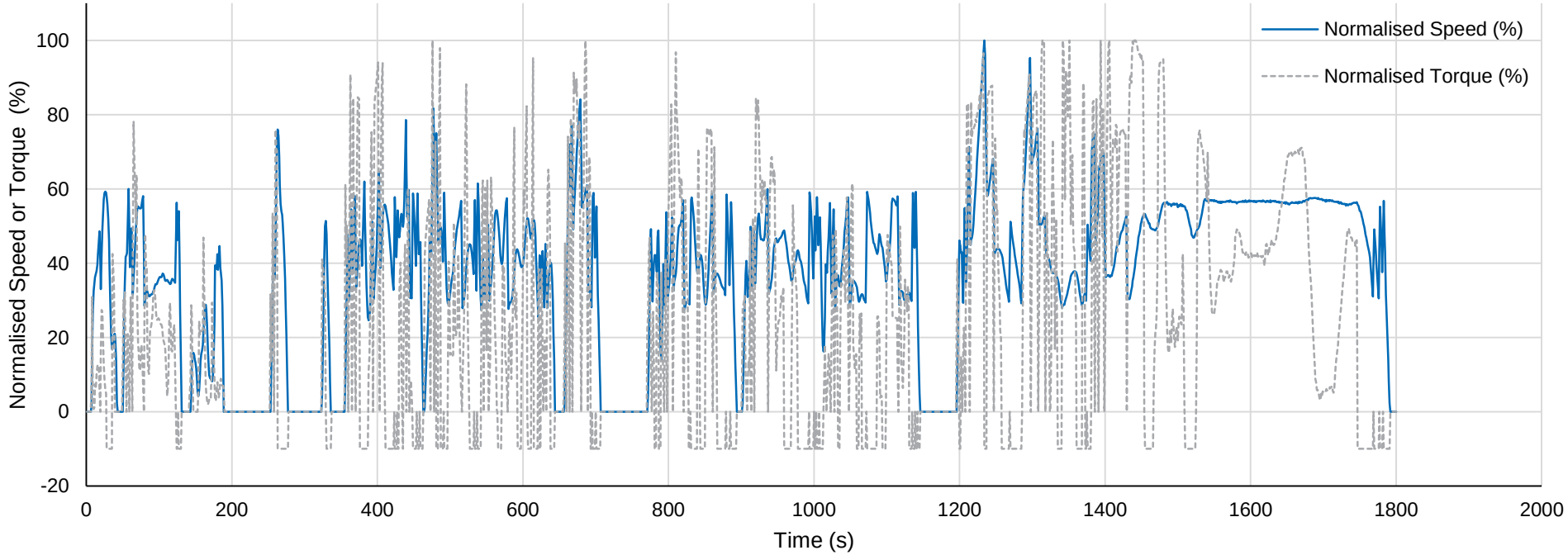


Source: EU Journal (9)

Both steady state and transient engine testing covers the majority of the engine speed-torque map, including operation at high loads

Engine testing cycles for Heavy Duty Euro VI – Transient (WHTC)

- WHTC testing is engine and aftertreatment only testing on an engine dynamometer, and it includes
  - A wide range of load and speed operation transiently
  - Cold start

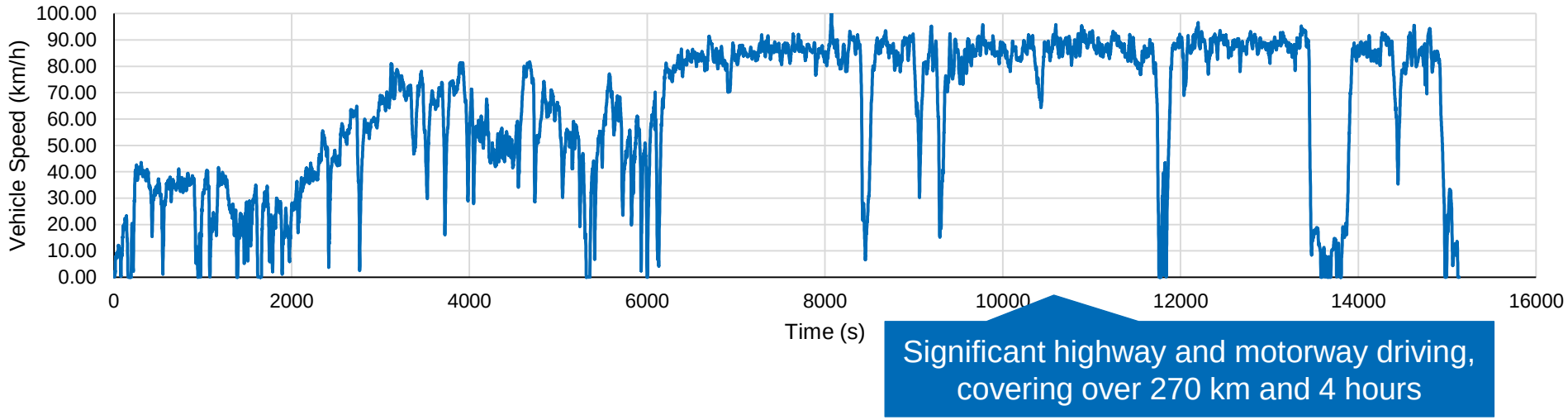


- The use of NTE zones and a wide ranging transient engine cycle mean that RDE at type approval / certification is not essential, as these and dyno cycles ensure compliant emissions during real driving. However RDE will be included as part of Euro VI-D certification, where it constitutes validation of engine dyno emissions and provides a benchmark for later ISC testing.

Source: EU Journal (9)

Vehicle testing, through PEMS on an RDE cycle, is only required for In Service Conformity through vehicle life, not type approval

Example In Service Conformity (ISC) test cycle for Heavy Duty Euro VI



- **ISC testing** is required for each engine family within 18 months of the first vehicle registration
  - Conformity tests are required at least every 2 years until 5 years after the end of vehicle production
  - The vehicle is fitted with PEMS and the payload must be between 10 and 100% of the maximum payload
  - No cold start requirement
  - The test must start urban with the following requirements:

>16 ton GVW	Urban	Rural	Motorway
Share of RDE cycle duration (%)	20	25	55
Average speed (km/h)	15 – 30	45 – 70	>70
Max speed (km/h)	50	75	-

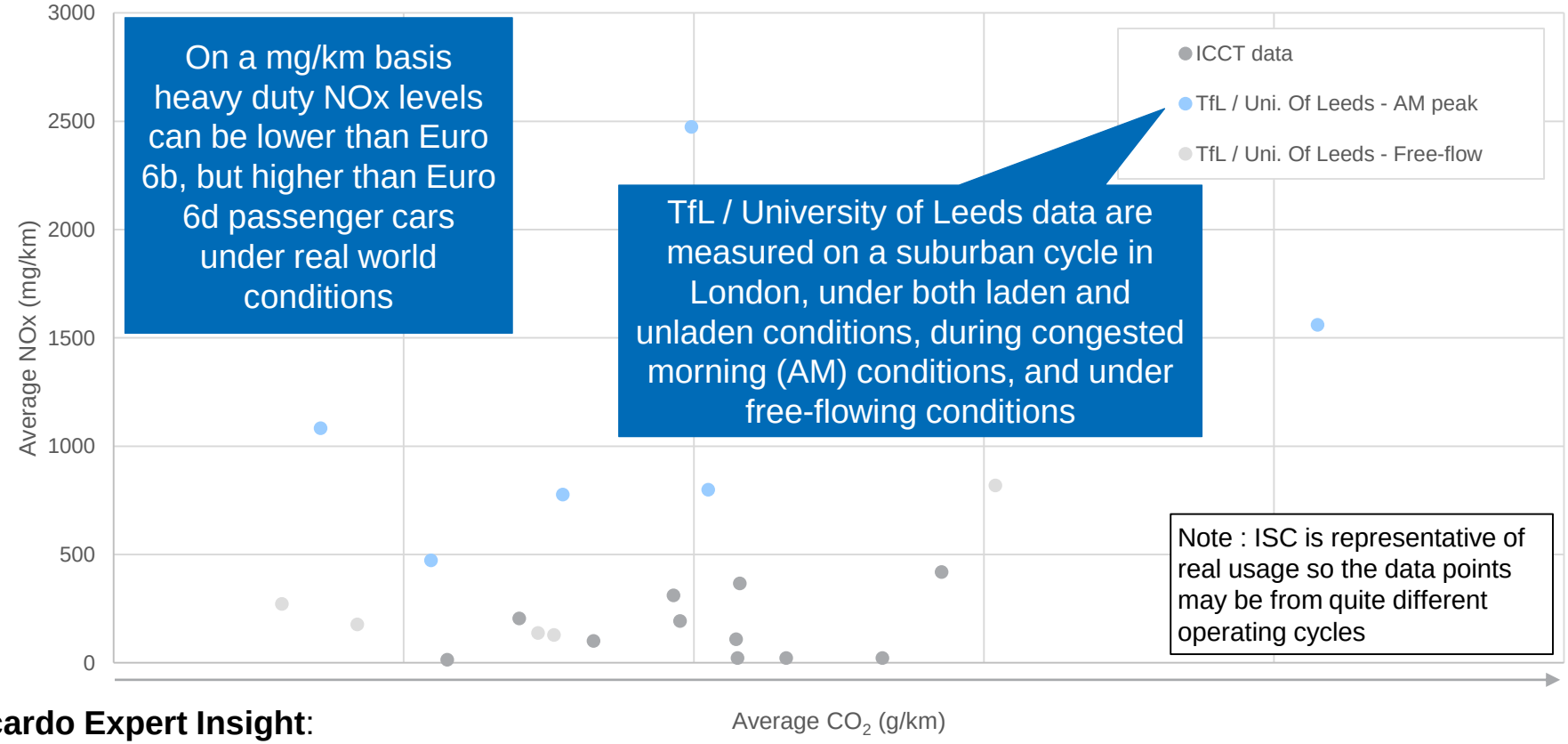
Source: Ricardo, Ricardo EMLEG (1); EU Journal (9)

Contents

Only a limited set of Heavy Duty emissions data under real world road conditions is published

Heavy Duty Diesel NOx (mg/km) – Euro VI

Data are measured on a variety of class rigid, artic, and bus applications on real world cycles, either on-road with PEMS or on chassis dynamometer



Ricardo Expert Insight:

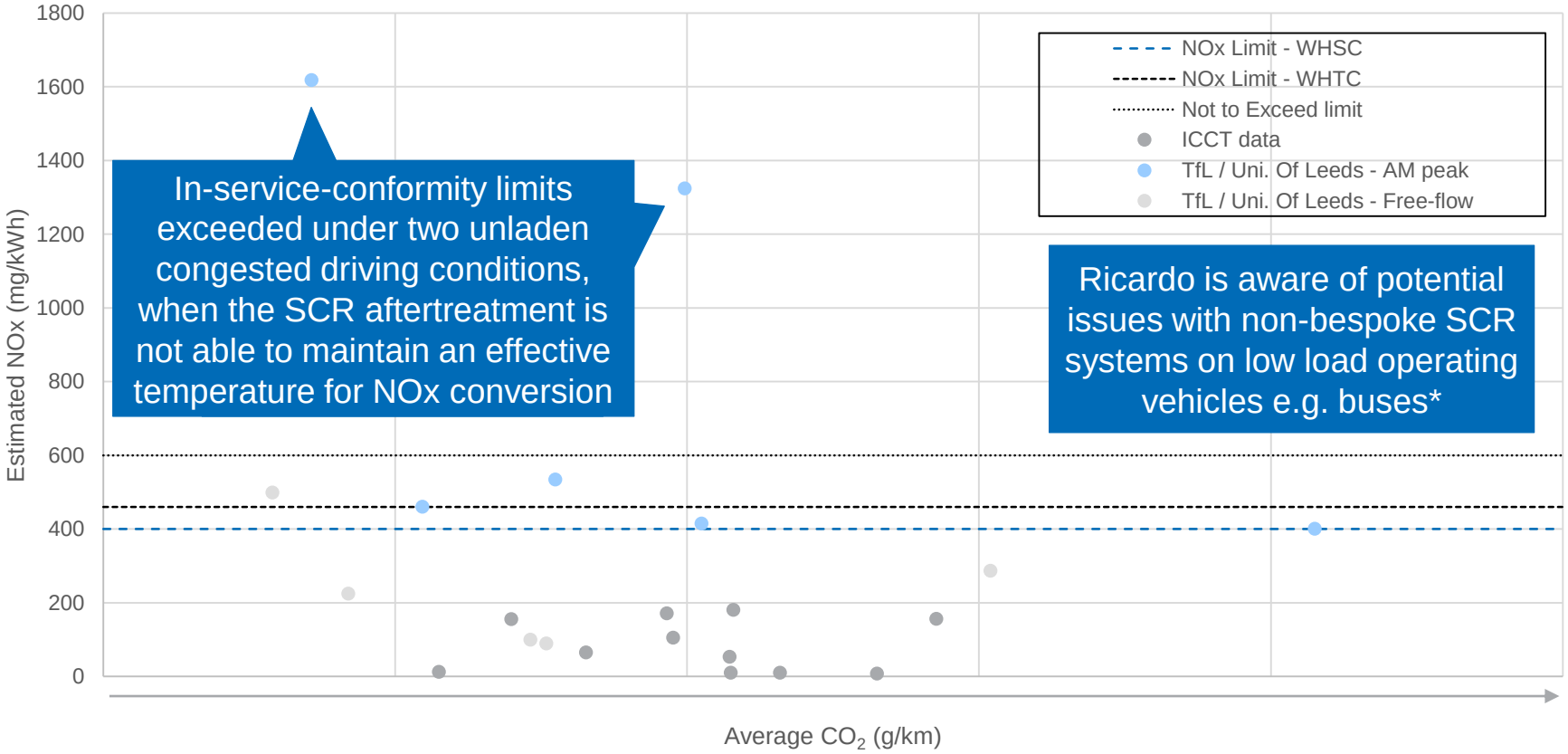
NO_X emissions of Heavy Duty (HD) diesel vehicles are low and are reducing, mostly due to SCR aftertreatment systems. SCR NO_X conversion efficiency is high when engines operate at high load. HD engines operate under high load for the majority of the HD duty cycle; therefore NO_X is kept at a minimum.

Source: References as listed in Appendix 3

Published heavy duty NOx data meets in-service conformity NOx limits, except under unladen congested traffic conditions

Heavy Duty Diesel NOx (mg/kWh) – Euro VI

- NOx in terms of mg/kWh – These data are estimated assuming 45% engine efficiency from the mg/km data presented on the previous page

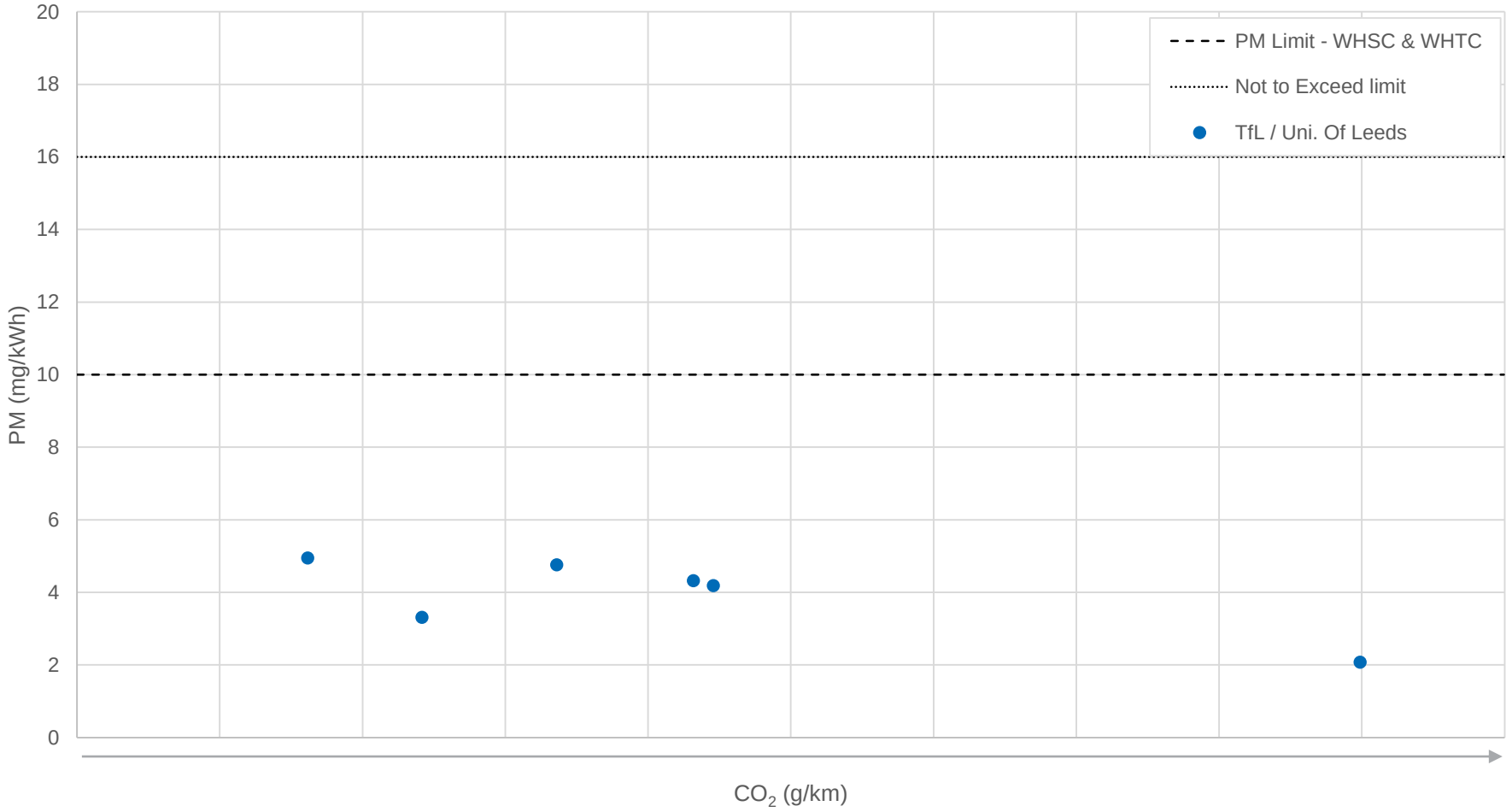


*Retrofit aftertreatment systems have the potential to be at least as effective at NOx control as standard fit aftertreatment systems. As retrofit systems are typically designed specifically for the application they may be more effective. For example: Ricardo PEMS measurement of buses showed that Euro III vehicles with retrofit aftertreatment showed more effective NOx control than Euro V buses with standard fit aftertreatment[27]

Source: References as listed in Appendix 3; Ricardo (27)

Only a limited set of Heavy Duty PM data under real world road conditions is published, but all is well within Euro VI limits

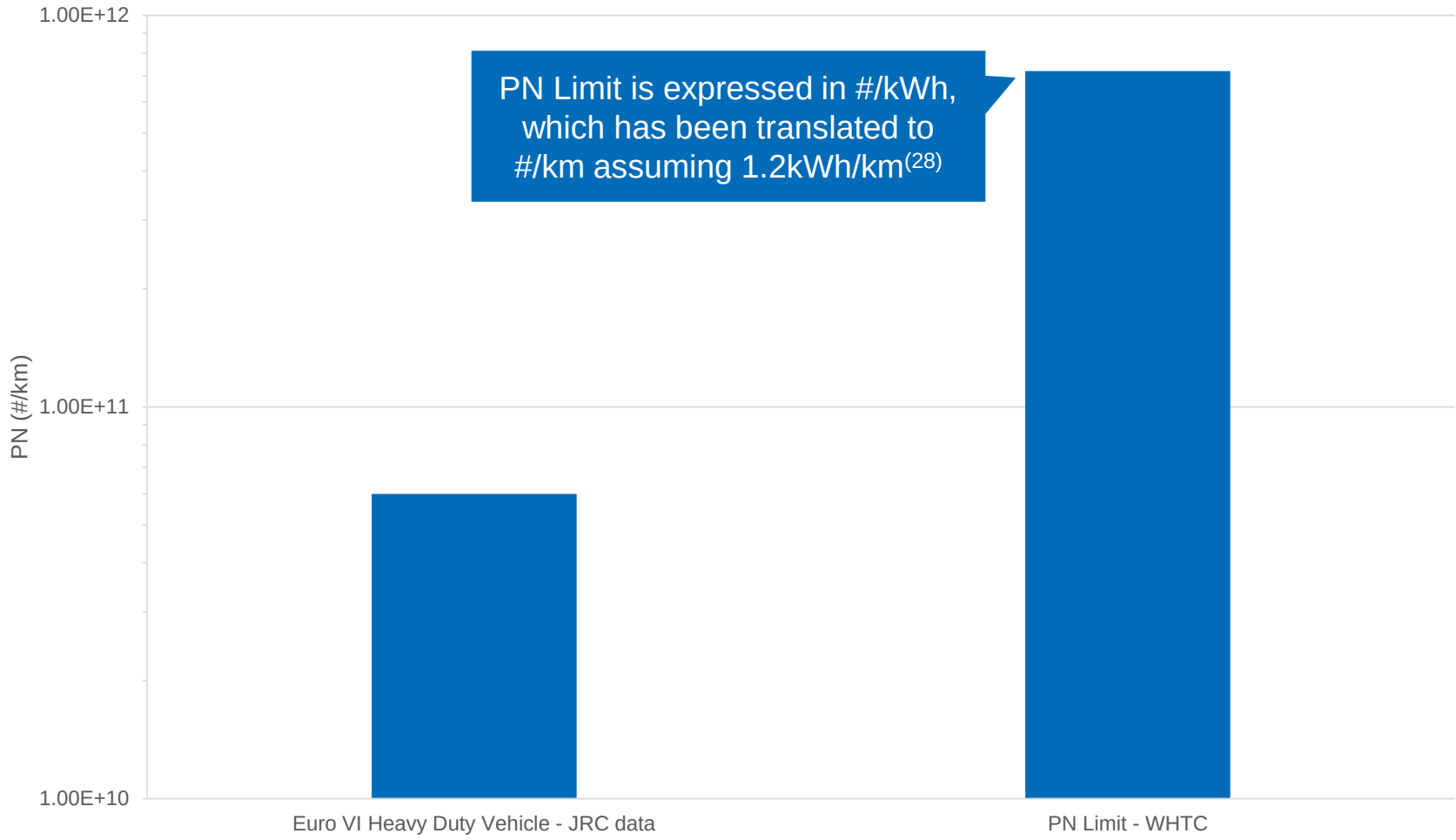
Heavy Duty Diesel PM – Euro VI Real World Data



Source: Reference as listed in Appendix 3. Note: The source does not state if the PM measurements are equivalent to filter-based measurements

The one published Euro VI PN real world cycle measurement study shows PN is an order of magnitude below the PN limit

Euro VI Heavy Duty – Real world cycle



Source: Reference 28 Vehicle Emission Factors of Solid Nanoparticles in the Laboratory and on the Road using PEMS, JRC, Dec 2015

Real world heavy duty NOx emissions are similar to test bed cycles and meet Euro VI limits

Actual emissions for Euro VI final

- HD Diesel emissions testing has covered a wide range of load and speed operation, which results in real world emissions similar to test bed results
- Published heavy duty NOx data meets in-service conformity NOx limits, except under some unladen congested traffic cases when the SCR aftertreatment may not able to maintain an effective temperature for NOx conversion
- Specific configuration and calibration of the emissions control systems is required for diesel NOx control, especially to ensure SCR operating temperature achieves high NOx conversion efficiency
- PM and PN are well within Euro VI limits under real world conditions

Euro VI Emissions Limits - Diesel			
Emissions		**Diesel**	**Technical Solution**
Oxides of Nitrogen	NO_x (mg/kWh)	✓	EGR + SCR*
Particulate Matter	PM (mg/kWh)	✓ (not legislated on ISC)	DPF + DOC
Particle Number	PN (#/kWh)	✓	DPF
Ammonia	NH_3 (ppm)	✓	ASC
Carbon Monoxide	CO (mg/kWh)	✓	DOC
Total Hydrocarbons	THC (mg/kWh)	✓	-
Non-Methane Hydrocarbons	NMHC (mg/kWh)	-	-

* Specification and calibration of engine and aftertreatment NOx control systems are critical for compliance

Contents

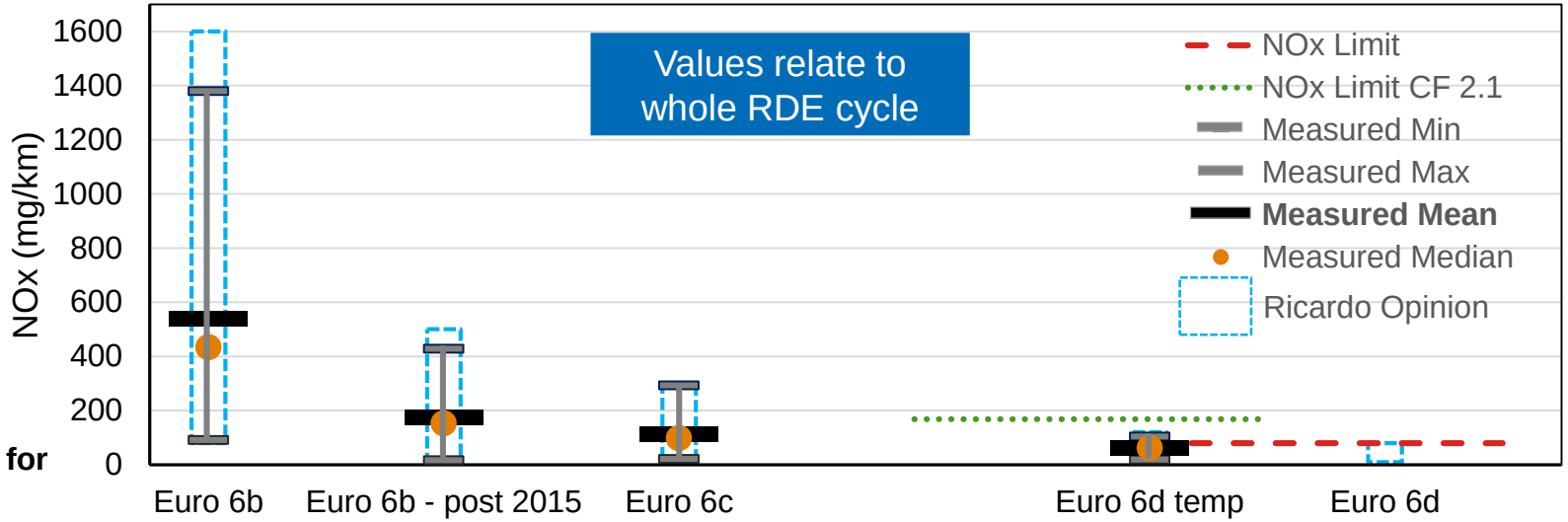
The latest solutions applied to light-duty vehicles are effective at meeting Euro 6 emissions limits under real world driving

Light-duty Vehicles

- Although there are a limited number of Euro 6c and 6d-temp ready vehicles to date, the evidence suggests that the technical solutions applied to Euro 6d will achieve regulated conformity factors under real world driving in moderate RDE temperature and altitude conditions, which are designed to cover the majority of European driving conditions
  [see page 51 for moderate conditions within the broader RDE criteria]
  - The NOx conformity factors (CF) are 2.1 for Euro 6d-temp and ≤ 1.5 for Euro 6d-final
  - The PN CF are ≤ 1.5 for Euro 6d
- The evidence indicates that real world diesel NOx emissions are substantially reduced by successive levels of Euro 6 legislation, from Euro 6b to Euro 6d-temp
- The control of emissions in Euro-6d vehicles is more robust than observed with Euro-6b vehicles across the range of driving conditions studied, and sensitivity of exhaust emissions to real driving, and RDE, is reduced at Euro 6d-temp
- Specific configuration and calibration of the emissions control systems is required for real world diesel NOx control, e.g.:
  - Using significant low pressure and high pressure EGR across the speed and load range
  - Ensuring SCR operating temperature permits high NOx conversion efficiency
  - Options include combined LNT and SCR aftertreatment systems
- Real world diesel PN data for Euro 6c and 6d-temp vehicles are within the Euro 6 conformity factors due to fitment of DPFs
- The data presented suggests that fitment of a GPF is likely to be required for gasoline vehicles to meet Euro 6d PN emissions requirements on all RDE cycles

The stages of Euro 6 introduction show a progressive reduction in real world driving NOx emissions

NOx under real world test conditions



Type approval implementation dates for M-class vehicles

Emission Standard	Homologation Method	OBD Standard	Real Driving Emissions	2015	2016	2017	2018	2019	2020
EU6b	NEDC	6-1	Voluntary Monitoring						
EU6c	WLTC	6-2	Voluntary Monitoring						
EU6d-temp	WLTC	6-2	Temporary CF = 2.1						
EU6d	WLTC	6-2	Final CF ≤1.5						

Measured values are the range of emissions from the studies presented in this report together with Ricardo test data.
Ricardo opinion estimates a representative range of emissions from certified vehicles during on road RDE testing
Ricardo opinion values relate to whole RDE cycles, not part RDE cycles (i.e. urban)
Ricardo opinion expects there to be parity between the WLTC lab certification value and the RDE requirement for Euro 6d
Euro 6 b – post 2015 are selected recent vehicles which meet Euro 6 NOx levels under at least one real driving test cycle. These are post 2015, however some other Euro 6b vehicles post 2015 have measured emissions which do not meet Euro 6 NOx levels for any real driving and these are included in *Euro 6b*

The latest solutions applied to heavy-duty vehicles are effective at meeting Euro VI emissions limits under real world driving

Heavy-duty Vehicles

- NO_X emissions of Heavy Duty (HD) diesel vehicles are low and are reducing, mostly due to the effect of SCR aftertreatment systems
  - SCR NO_X conversion efficiency is high when engines operate at high load
  - HD engines operate under high load for the majority of the HD duty cycle
- Published heavy duty NOx data meets in-service conformity NOx limits, except under some unladen congested traffic cases when the SCR aftertreatment may not be able to maintain an effective temperature for NOx conversion
  - Specific configuration and calibration of the emissions control systems is required for diesel NOx control, especially to ensure SCR operating temperature achieves high NOx conversion efficiency
- PM and PN are well within Euro VI limits under real world conditions

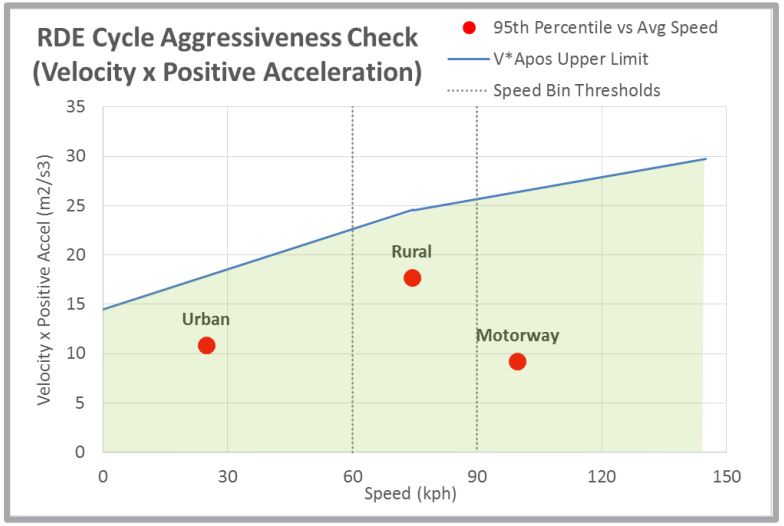
Contents

To be valid, the RDE trip must meet distance, trip composition and average speed requirements as well as dynamic boundary conditions

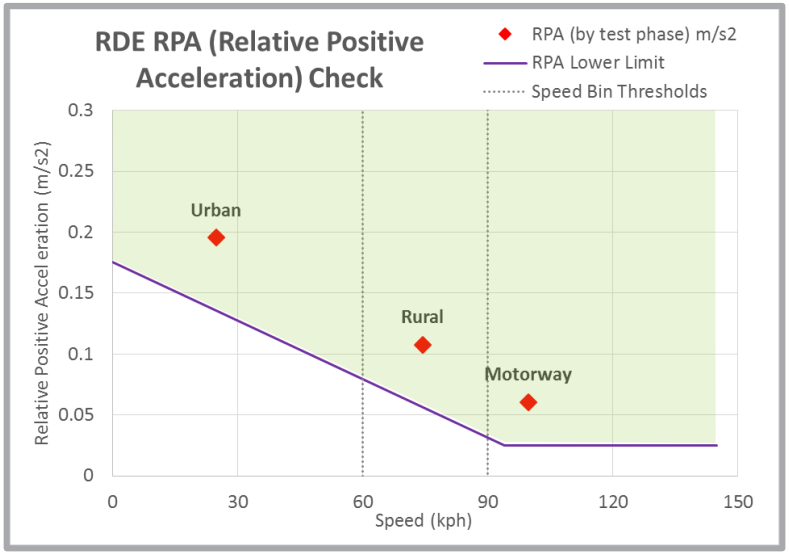
RDE boundaries and compliance (1 of 2)

Trip Specifics		Provision set in the legal text
Total trip duration		Between 90 and 120 minutes
Distance	Urban	>16 km
	Rural	
	Motorway	
Trip Composition	Urban	29% to 44% of distance
	Rural	23% to 43% of distance
	Motorway	23% to 43% of distance
Average Speeds	Urban	15 to 40 kph
	Rural	Between 60 and 90 kph
	Motorway	>90 kph (>100 kph for at least 5 minutes)

- In addition to satisfying the requirements in the table, the RDE tests are prevented from having excessive aggressiveness or being too mild
  - For the test to be valid the 95th percentile of V*a of each section of the RDE trip must be:
    - Below the V*a (velocity x acceleration) line
    - Above the RPA (relative positive acceleration) line



Example data points from a moderate RDE



Source: Ricardo analysis of regulation

Additional criteria for altitude, temperature and stop percentage must also be achieved

RDE boundaries and compliance (2 of 2)

Parameter		Provision set in the legal text
Payload		≤ 90% of maximum vehicle weight
Altitude	Moderate	0 to 700m
	Extended	Between 700 to 1,300m
	Difference	No more than 100m altitude difference between start and finish
	Cumulative gain	1200 m/100km
Ambient Temperature	Moderate	0°C to 30°C
	Extended	From -7°C to 0°C and 30°C to 35°C
Stop Percentage		Between 6% and 30% of urban time
Maximum Speed		145 km/h (160 km/h for 3% of motorway driving time
Dynamic boundary conditions	Maximum metric	95th percentile of v*a (speed x positive acceleration)
	Minimum metric	RPA (relative positive acceleration)
Use of auxiliary systems		Free to use as in real life (operation not recorded)

If a data point falls within the extended conditions, the emissions measured have to be divided by a factor of 1.6

Any data point falling outside the boundary conditions makes the whole trip invalid

Legislation allows automakers to carry out up to 50% of the RDE type-approval tests themselves, witnessed by a technical service company

Source: Ricardo analysis of regulation

Passenger cars must satisfy 5 year or 100,000 km emissions durability, while RDE is expected to include cold and warm starts

Further passenger car Euro 6 considerations (1 of 2)

- **Cold engine starts**
  - Cold start periods are included in RDE tests (previously excluded from emissions evaluation[5 - 9.6], has been included in the regulation as part of RDE package #3[29])
    - Cold start periods are defined as the first 5 minutes or when the engine coolant reaches 70 °C for the first time[5]
  - The average speed during the cold start period (including stops) is 15 – 40 km/h (the Urban phase) and maximum speed during cold start shall not exceed 60 km/h
- **Regeneration of emissions control devices**
  - When periodic regeneration occurs within an RDE test, the test may be repeated but if a regeneration occurs in the second test, the emissions must be included in the RDE test result.
    - The Ki factor derived from on-dynamometer testing is also applicable to RDE results[21]
- **Durability**
  - Manufacturers must[3]
    - Prove that all new vehicles and new pollution control devices comply with the legislation and can meet the emission limits during a vehicle's normal life;
    - Ensure that pollution control devices can last 160 000 km (durability testing) and are checked after five years or 100,000 km, whichever is the sooner;
- **RDE Monitoring**
  - For Euro 6c monitoring of RDE cycles, the conformity factors are required to be reported

Source: Ricardo EMLEG (1), EU Regulation (3), EC (5), EC (21), EC (29)

Activation of the OBD system will occur if the Euro 6 OBD threshold final limits are exceeded, inhibiting any high emissions driving

Further passenger car Euro 6 considerations (2 of 2)

- **On Board Diagnostics (OBD)**
  - From 1st September 2017 all passenger cars required full OBD requirements with the final threshold limits

Euro 6 OBD Threshold Emissions Limits - Final[1]			
Emissions		**Gasoline (Positive Ignition)**	**Diesel (Compression Ignition)**
Oxides of Nitrogen	NO_x (mg/km)	90	140
Particulate Matter	PM (mg/km)	12	12
Particle Number*	PN (#/km)	-	-
Hydrocarbons + NOx	HC + NOx (mg/km)	-	-
Carbon Monoxide	CO (mg/km)	1900	1750
Total Hydrocarbons	THC (mg/km)	-	-
Non-Methane Hydrocarbons	NMHC (mg/km)	170	290

  - * It is likely that PN OBD will be required in the near future
- **Limitations of emissions limits presented in RD18-000697 (this report)**
  - Within the legislation presented, only Euro 6b to Euro 6d are considered for internal combustion engine vehicles
  - Hybrid vehicles are not considered

Source: Ricardo EMLEG (1)

Heavy duty in-service conformity tests for Euro VI do not consider cold start emissions, but do require strict durability requirements

Further heavy duty Euro VI considerations (N3 or GVW >16 tons)

- **Warm up** is not assessed during in-service conformity (or demonstration tests)[8]
  - Trip duration starts once the coolant temperature reaches 70 °C for the first time, or the coolant temperature stabilises, or 15 mins
  - PN
    - Aftertreatment regeneration is included as a factor in the hot test results only
    - PN values are weighted 14% cold test to 86% hot test
- **Durability requirements**
  - Manufacturers must ensure that vehicles satisfy the emissions limits up to 700,000 km or seven years, which ever comes sooner

Source: Ricardo EMLEG (1); EU Legislation (8)

Contents

Official RDE data was not available, so results from published testing programs were used – which focused on diesel NOx

- **Official RDE data sources**
  - The Euro 6c RDE emissions monitoring data is required to be accessible publically from all OEMs
    - Data is supposed to be available from
      - ACEA [18] – The majority of vehicle emissions data is purportedly contained within this website, however the vehicle details are required to access the data require ownership of each vehicle model for which the data is required
      - Renault[19] – Registered vehicle ownership details are required to be able to access any emissions data
      - PSA[20] – Emissions (NOx) data not available until summer 2017
- **Public domain searches**
  - Public domain data was searched for using the tool Ricardo Powerlink as well as general web searches
    - This considered technical and academic papers as well as industry articles from the largest automotive database globally
  - While many papers discuss RDE testing and future engine technology for RDE testing, relatively few provide test results of representative Euro 6 vehicles
  - Due to public interest in diesel NOx emissions in recent years, the majority of public data is based around diesel NOx testing, with little data available for other emissions or gasoline
  - All available emissions test results for certified or representative Euro 6 vehicles have been included in the plots presented

70 articles of relevance were reviewed to determine if they contained suitable Euro 6 data

- The following searches were carried out using Ricardo Powerlink

Search term	Limits	Number of abstracts reviewed	Number of articles reviewed	Comments
rde OR pems	2016 +	176	61	
pems > Heavy duty > Euro VI	2010+	36	9	Heavy duty not to exceed limits introduced in 2013, so time frame extended to 2010+

- Google searches were performed for a number of search terms including combinations of “rde”, “pems”, “euro 6”, but did not yield any articles of relevance not already found within Ricardo Powerlink

Public domain data used in the analysis are predominately for Euro 6b vehicles from a variety of testing programmes

- Public domain data from real driving emissions has been used:

Source	Report	RDE Emissions Measured	Number of Euro 6 passenger cars tested	Fuel type	Comment
TNO, October 2016[10]	NOx emissions of fifteen Euro 6 diesel cars: Results of the Dutch LD road vehicle emission testing programme 2016	NO_x and NH_3	15	Diesel only	Multiple RDE cycles; Euro 6b; Some Euro 6c
UK Department for Transport 2016[11]	Vehicle emissions testing programme: conclusions	NO_x	19	Diesel only	Single RDE value; Euro 6b
ICCT / German Government, December 2016[12]	NOX emissions from heavy-duty and light-duty diesel vehicles in the EU: Comparison of real-world performance and current type-approval requirements	NO_x	30	Diesel only	Single RDE value; Euro 6b
ICCT / Emissions Analytics, September 2016[13]	On-road testing of CO2 and exhaust emissions from Euro 6 passenger cars in the EU: Technical Report	NO_x and PN	5	Diesel and gasoline	Multiple RDE cycles; Euro 6b
Deutsche Umwelthilfe, 2017[15]	NOx and CO2 measurements for Euro 6 cars in Real Driving Mode	NO_x	15	Diesel	Single RDE value; Euro 6b
Transport for London / University of Leeds, UK, 2017[25]	In Service CO2 and NOX Emissions of Euro 6/VI Cars, Light- and Heavy-dutygoods Vehicles in Real London driving: Taking the Road into the Laboratory	NOx	12	Diesel & gasoline	Tested over urban and suburban real driving (TfL London Drive Cycle)

Ricardo testing provided Euro 6c and 6d results and the expectations of actual Euro 6 emissions

- Ricardo RDE test data has informed the Euro 6d emissions position
  - Ricardo have tested vehicles certified to Euro 6c and research “6d-temp ready” vehicles over a variety of RDE cycles
    - These vehicles are fitted with a variety of aftertreatment systems, including for NOx control
      - LNT only
      - SCR only
      - LNT + SCR

  - Ricardo have developed a range of RDE cycles within the European Commission boundaries for compliance
    - The results presented are a mixture of on road testing, and chassis dynamometer testing
      - The chassis dynamometer testing is a recreation of valid on road RDE tests with appropriate road loads, but allows measurement of the full range of emissions with greater accuracy than is possible with PEMS equipment
        - Particulate mass is measured on a chassis dynamometer, not with PEMS
  - Ricardo technical specialist opinion and involvement in the development of future Euro 6d vehicles guides the expectations of how emissions are expected to develop under Euro 6 legislation

Euro 6 NOx control requires a mix of solutions including high and low pressure EGR, LNT and multiple SCRs

NOx control technology options

Technology	How it works	Comment
HP EGR	• High pressure exhaust gas is cooled and recirculated from pre aftertreatment to post compressor • EGR replaces some of the oxygen in the intake air with inert gas, which cannot combust or react with the nitrogen in air, together with cooling the combustion, resulting in lower NOx emissions	EGR cannot meet Euro 6 NOx requirement, but its use reduces the NOx conversion requirements of the LNT or SCR (and associated urea consumption)
LP EGR	As HP EGR, but the low pressure EGR is taken post aftertreatment, cooled and fed in pre-compressor	Allows EGR to be used over a wider engine map and at greater rates than just HP EGR
DOC	Oxidises NO to NO_2 to allow LNT and SCR to work effectively (Controls HC and CO, and produces an exothermic to assist with DPF regeneration)	
LNT	• Stores NO_2 and converts it to N_2 during regeneration • High NOx conversion efficiency is limited to relatively low temperatures	Its application is suitable for vehicles operating at low temperatures, such as those with large, relatively low power engines (moderate BMEP), unless fitted together with a SCR
SCR	• Ammonia is used as the reductant to control NOx over the SCR catalyst • The SCR coating can be applied to a flow through substrate or a DPF. SCR on filter allows the catalyst to sit in a hot part of the exhaust allowing an early light off • For active SCR ammonia is injected upstream of the SCR catalyst	Highly effective NOx conversion efficiency within its operating temperature range, but less efficient at low temperature
Passive SCR (pSCR)	As SCR except the ammonia is supplied from an upstream LNT, not injected	

Source: Ricardo analysis; Hipp et al (16)

Contents

Public domain data used in the analysis are predominately for Euro VI heavy duty vehicles from a variety of testing programmes

- Public domain data from real driving emissions has been used:

Source	Report	RDE Emissions Measured	Number of Euro VI vehicles tested	Comment
Technical University Graz, 2013[23]	The rule of CO_2 and RDE in the future exhaust gas regulation for LDV and for HDV	NOx	1	Tested over a range of cycles with different average speeds
ICCT / VTT, Dec 2016[24]	NOx emissions from heavy-duty and light-duty diesel vehicles in the EU: Comparison of real-world performance and current type-approval requirements	NOx	11	
Transport for London / University of Leeds, UK, 2017[25]	In Service CO_2 and NOx Emissions of Euro 6/VI Cars, Light- and Heavy- duty goods Vehicles in Real London driving: Taking the Road into the Laboratory	NOx	2	Tested over urban and suburban real driving
CNH-Industrial, 2014[26]	HDCV - Euro VI accomplishment and the way ahead	NOx	3	On-road
Ricardo, 2015[27]	Use of PEMS on Heavy Duty Vehicles to Assess the Impact of Technology and Driving Conditions on Air Quality in Urban Areas	NOx	1	Short urban on-road route

Contents

Contributions to the Original Study

Contributors to this report and to the original study, conducted in June 2017, are listed below

Jon Andersson	Manager, Aftertreatment and Chemical Analysis Department; Global Technical Expert, Emissions Measurements and Standards
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Richard Osborne	Global Technical Expert, Gasoline Combustion
Mark Parrett	Project Engineer, Technology Strategy
Nick Powell	Manager, Technology Strategy
Roscoe Sellers	Chief Engineer, Light Duty Diesel Engines

References

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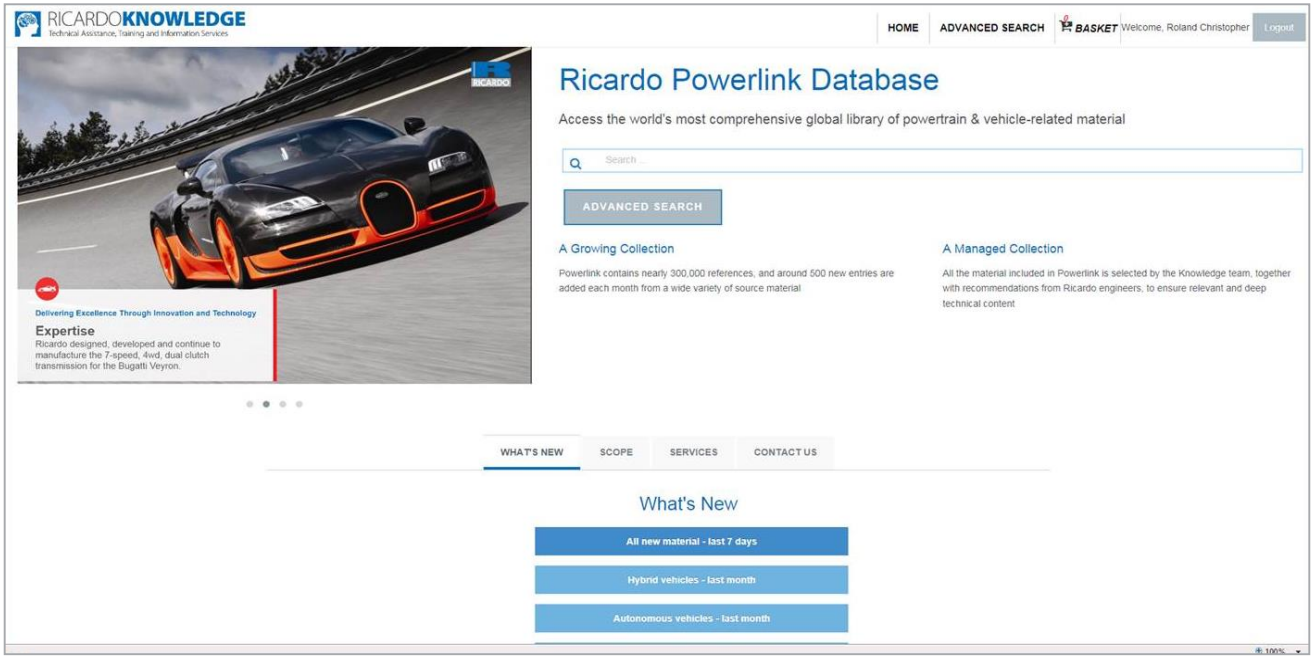

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Abbreviations

Abbr.	Explanation
ACEA	The European Automobile Manufacturers' Association
ASC	Ammonia Slip Catalyst
BMEP	Brake Mean Effective Pressure
CF	Conformity Factor (RDE Emissions / Legislated Limit)
CO	Carbon monoxide
CO_2	Carbon Dioxide
DOC	Diesel Oxidation Catalyst
DPF	Diesel Particulate Filter
EGR	Exhaust Gas Recirculation
EV	Electric Vehicle
GHG	Green House Gas
GPF	Gasoline Particulate Filter
GVW	Gross Vehicle Weight
HC	Hydrocarbons
HGV	Heavy Goods Vehicle
HP EGR	High Pressure Exhaust Gas Recirculation
ISC	In-service Conformity Testing
KPH	Kilometres Per Hour
LNT	Lean NOx Trap
LP EGR	Low Pressure Exhaust Gas Recirculation
MPG	Miles Per Gallon
NEDC	New European Drive Cycle
NG	Natural Gas
NH_3	Ammonia
NMHC	Non-methane hydrocarbons
NMOG	Non-methane organic gases
NO_2	Nitrogen Dioxide
NOx	Oxides of Nitrogen
NSC	NOx Storage (accumulation) Catalyst or LNT
NTE	Not To Exceed
OBD	On-board Diagnostics
OEM	Original Equipment Manufacturer
PEMS	Portable Emissions Measurement System
PHEV	Plug-in Hybrid Electric Vehicle
PM	Particulate Matter
PN	Particle Number
RDE	Real Driving Emissions
RPA	Relative Positive Acceleration
SCR	Selective Catalytic Reduction
SCRF	SCR coating on DPF
THC	Total Hydrocarbons
TWC	Three Way Conversion Catalyst
ULEZ	Ultra Low Emissions Zone
VGT	Variable Geometry Turbocharger
WGT	Wastegate Turbocharger
WHSC	World Harmonized Stationary Cycle
WHTC	World Harmonized Transient Cycle
WLTC	Worldwide harmonized Light vehicles Test Cycle
WLTP	Worldwide harmonized Light vehicles Test Procedure
ZEZ	Zero Emissions Zone