Recent studies on real driving emissions of diesel passenger cars

Two Concawe studies are commissioned to provide insight into the on-road emissions performance of the latest available diesel passenger cars.

Emissions have been the focus of worldwide legislation for more than twenty-five years. European emissions legislation has set limits for particulate matter (PM) and oxides of nitrogen (NO_x) emissions from diesel vehicles since the early 1990s, along with hydrocarbons (HC), which were initially included with NO_x until 2000, and carbon monoxide (CO). For diesel passenger cars, PM limits were first introduced with the Euro 1 standards in 1992. Since then the limits have become progressively tighter, reaching 4.5 mg/km for the Euro 6 (2014) standards. More recently the focus has expanded to include particle number (PN), and a limit of $6x10^{11}$ particles/km became effective for diesel vehicles from 2011 (new models) and 2013 (all models). NO_x emissions limits have also reduced steadily and for diesel Euro 6 vehicles the limit has reached 80 mg/km. Similarly stringent standards have been introduced in other parts of the world. The introduction of these limits, along with clean fuels and advanced vehicle and after-treatment technologies, has resulted in a substantial reduction in automotive particulate mass (PM) emissions with a corresponding improvement in air quality. Figure 1 shows the breakdown of sources of emissions of particulate (in this case $PM_{2.5}$) in urban areas in 2015.

Road transportation in 2015 only contributed 10% of total $PM_{2.5}$ emissions; only half of that value was due to exhaust particulate, with brake wear and tyre wear making up the other half. Domestic heating was a much bigger contributor to particulate emissions than vehicles in urban areas.

NO_x levels have not reduced as expected despite the limits mandated by the Euro standards.[1,2,3] As can be seen in Figure 2 on page 5, road transportation in 2015 accounted for more than 40% of NO_x emissions contributing towards non-compliance with air quality standards. Figure 3a on page 5 shows attenuation of air quality standards for NO_2 in 2010; zones of compliance are shown in green, non-compliance shown in red and uncertain compliance shown in yellow. A Concawe study carried out with Aeris Europe[4] suggested that by 2030 these areas of non-compliance would be reduced down to smaller discrete islands (Figure 3b). This study made assumptions about the NO_x levels that could be achieved, and these will be updated with new data based on the Ricardo study described below.

Part of the reason that real-world NO_x levels have not come down in line with expectations is that emissions regulations for passenger vehicles have traditionally been based on the New European Driving Cycle (NEDC). Amid concerns that this test cycle does not represent closely enough real road driving in terms of CO_2 and other emissions levels including NO_x, two new test procedures are under development—the Worldwide harmonized Light duty Test Procedure

Figure 1 Sources of $PM_{2.5}$ emissions in urban areas in 2015

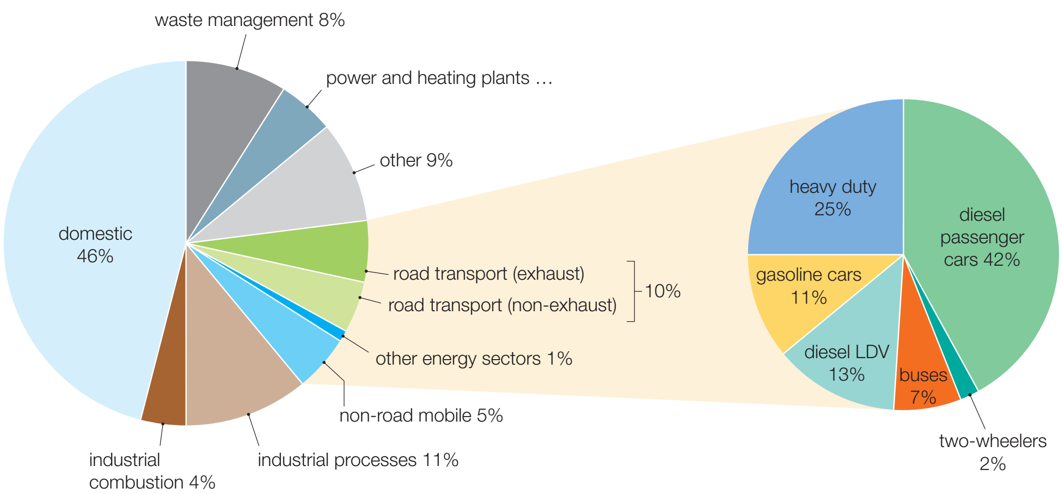
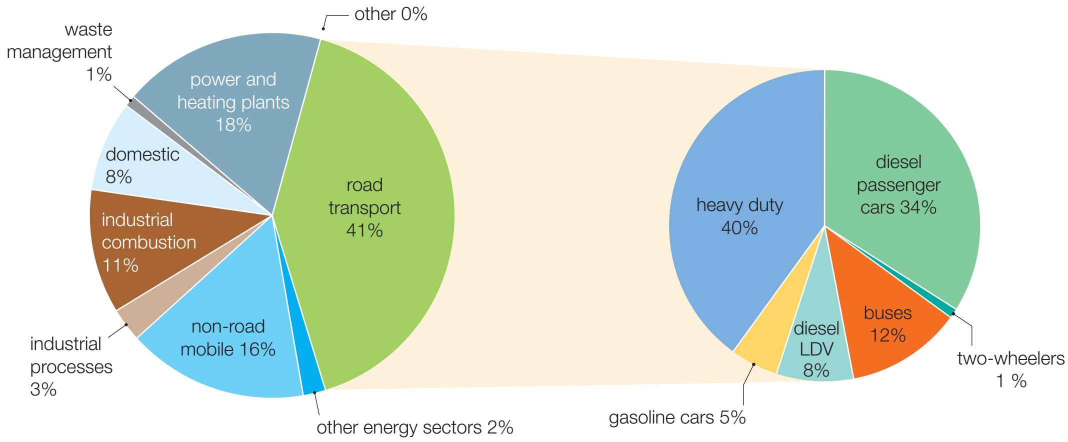


Figure 2 Sources of NO_x emissions in 2015



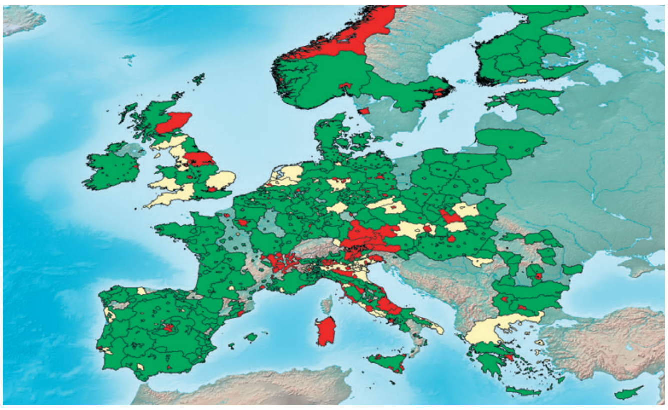
(WLTP), for use on the chassis dynamometer, and the Real Driving Emissions (RDE) procedure for on-road use. Going forward, these tests will be used to certify vehicles, so there is much interest in how they will compare with the current NEDC certification test and in whether or not new Euro 6b+ vehicles will meet emissions limits under the new procedures. It is expected that the challenges will include:

- urban driving conditions under which selective catalytic reduction (SCR) after-treatment technologies may not rapidly reach an efficient operating temperature;
- high load conditions under which exhaust temperatures may become too high for lean NO_x traps technologies to be effective, and high flow rates at high load which may diminish performance of smaller SCR volume solutions; and
- low temperatures which may limit the use of exhaust gas recirculation (EGR)—another method used to reduce NO_x emissions.

One of the enablers to being able to carry out testing of more real-world on-road driving has been the development of portable emissions measurement systems (PEMS) which are able to measure gaseous and particle number (PN) emissions under real driving conditions. The RDE test protocol was adopted in 2016 together with the not-to-exceed (NTE) limit for NO_x, published in the first two packages of EU legislation.[5,6] Two extra Euro 6 vehicle stages will be introduced as a consequence: Euro 6d-temp as of September 2017 with a NO_x conformity factor (CF) of 2.1; and the full Euro 6d as of January 2020 with a NO_x CF of 1.5 or less. The limits apply to both an urban por-

Figure 3 Attenuation of air quality standards for NO_2

(a) 2010



(b) 2030 projection

Table 1 Implementation timetable for RDE and WLTC procedures

Implementation dates for M-Class vehicles

Emission Standard	Homologation Method	OBD Standard	Real Driving Emissions	2015	2016	2017	2018	2019	2020	2021
				J F M A M J J A S O N D	J F M A M J J A S O N D	J F M A M J J A S O N D	J F M A M J J A S O N D	J F M A M J J A S O N D	J F M A M J J A S O N D	J F M A M J J A S O N D
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

tion of the test as well as the total test NO_x results. Part of the RDE procedure involves post-processing the raw data using EMROAD which works on the principles of moving average windows (MAWs). The test protocol also defines limits for the environmental and driving dynamic boundary conditions.

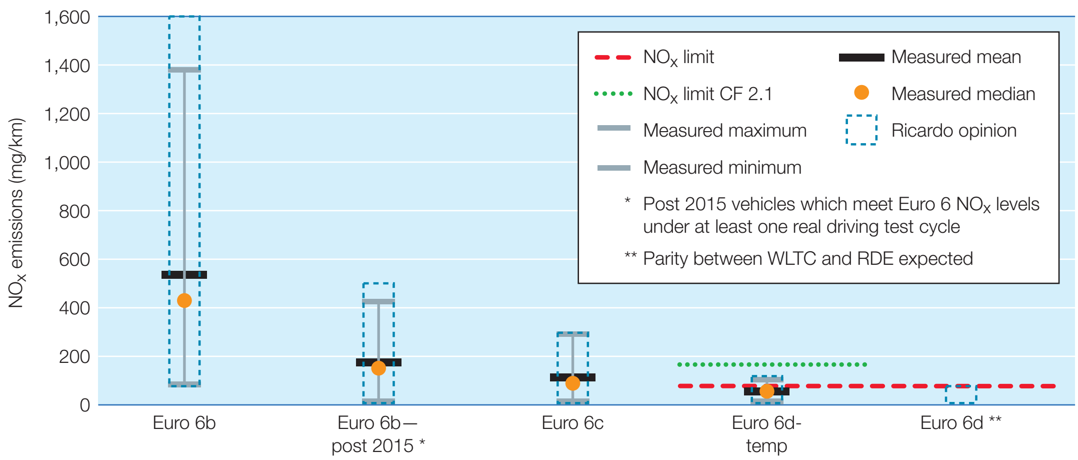
In addition to the RDE test, a new chassis dynamometer cycle, the WLTC cycle has also been developed which is longer than the NEDC and is expected to be more severe as it contains a mix of far more realistic driving characteristics and a range of speeds. The timetable for these developments is shown in Table 1.

Ricardo study on 'Expectations for actual Euro 6 vehicle emissions'

This study was carried out during the first half of 2017 and its goal was to show the expectations for actual Euro 6 vehicle real driving emissions. The data presented is from a variety of public domain sources (Euro 6b and a few Euro 6c) as well as Ricardo in-house data which is mainly Euro 6c (and some vehicles which appear to be Euro 6d-ready). At the time of study, and also at the time of writing, there are few certified Euro 6d diesel vehicles. The results are from vehicles tested over a variety of on-road real-world cycles (see Figure 4). The measured values (the hashed areas) are shown as well as Ricardo's opinion of the total range of data. As the status technology goes from Euro 6b to Euro 6c to Euro 6d-temp a reduction in the NO_x levels is observed, as can be seen from the figure.

Figure 4 Diesel NO_x emissions under real-world test conditions (0°C to 30°C, 0 to 700 m altitude)

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



Type Approval dates: *September 2014–August 2017* *April 2016–August 2017* *September 2017–December 2019* *January 2020–*

The main conclusion from this study is that Euro 6d compliance is expected to be possible with the right combination of engine and after-treatment systems.

Some of these after-treatment systems have been tested in another programme which Ricardo has been running for Concawe, as described below.

Concawe RDE test programme

Three modern diesel vehicles (see Table 2) were installed on a chassis dynamometer and tested over the NEDC, WLTC and US06 drive cycles. On-road RDE tests were also carried out on these vehicles. All the testing was carried out at and around Ricardo's facility at Shoreham-by-Sea in the UK. The test vehicles were purchased second-hand from the German market but all of them had been driven for around 5,000–10,000 km and were equipped with modern after-treatment systems with different configurations.

The CD and RDE testing was conducted on a market diesel fuel which fully met the EN590 requirements. Selected properties are shown in Table 3.

Table 2 Technical details of the test vehicles

	Car A	Car B	Car C
Emissions class	M1	M1	M1
Size category	C	D	E
Emissions certification	Euro 6b	Euro 6b	Euro 6c
Year of registration	2016	2015	2016
Cylinders/valves	3/12	4/16	4/16
Displacement (litres)	1.50	1.97	1.95
Output (kW)	85	140	143
Emissions controls	High Pressure EGR, LNT, DPF, SCR	High & Low Pressure EGR, urea-SCRF*, ASC	High & Low Pressure EGR, urea-SCRF*, SCR/ASC

* Car B used closed-loop control for urea (aq) dosing, Car C open-loop control

Table 3 Test fuel properties

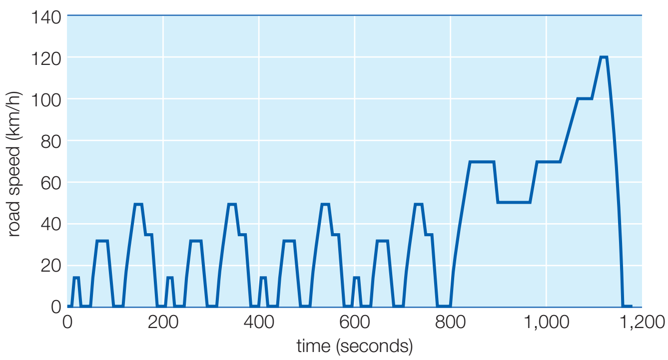
Property	Method	EN590 min.	EN590 max.	Fuel
CN	EN ISO 5165	51	-	53
Density (kg/m^3)	EN ISO 12185	820	845	822
Sulphur (mg/kg)	EN ISO 20846	-	10	7.9
Viscosity at 40°C (mm^2/s)	ASTM D445	2	4.5	2.28
FAME (v/v%)	EN 14078	-	7	4.1
IBP (°C)	ASTM D86	-	-	160
T50 (°C)	ASTM D86	-	-	255
T95 (°C)	ASTM D86	-	360	344
FBP (°C)	ASTM D86	-	-	355

Chassis dynamometer and real driving emissions test cycles

Three chassis dynamometer drive cycles were tested, two European and one from the USA. Unusually, during the current European regulatory phase, Euro 6c, two cycles may be used: the legacy NEDC (Figure 5a), which has only moderate transient character, and the newly developed WLTC (Figure 5b) which contains a mix of far more realistic driving characteristics and a range of speeds. A third, US cycle, the US06, which was developed to specifically highlight the impacts of high speed,

Figure 5 Chassis dynamometer test cycles

(a) NEDC



(b) WLTC

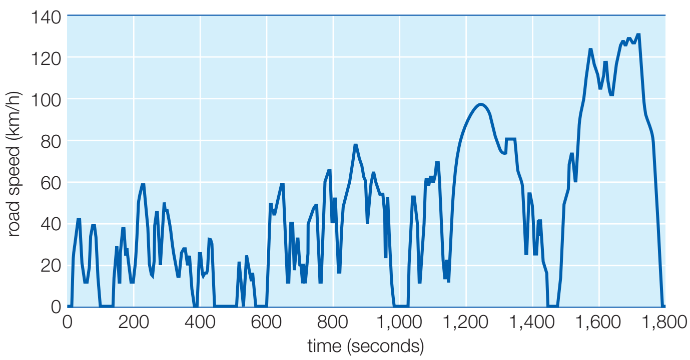
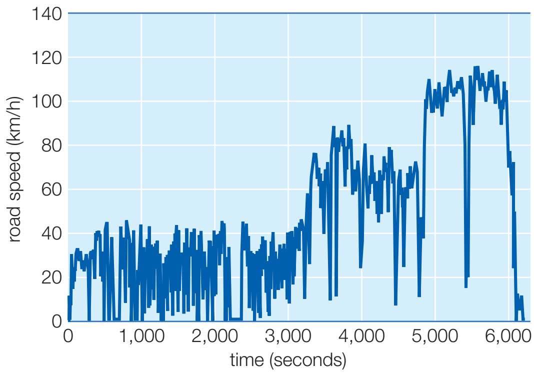


Figure 6 The Ricardo RDE route

(a) Map of the RDE route

(b) Speed/time plot (eastbound route)



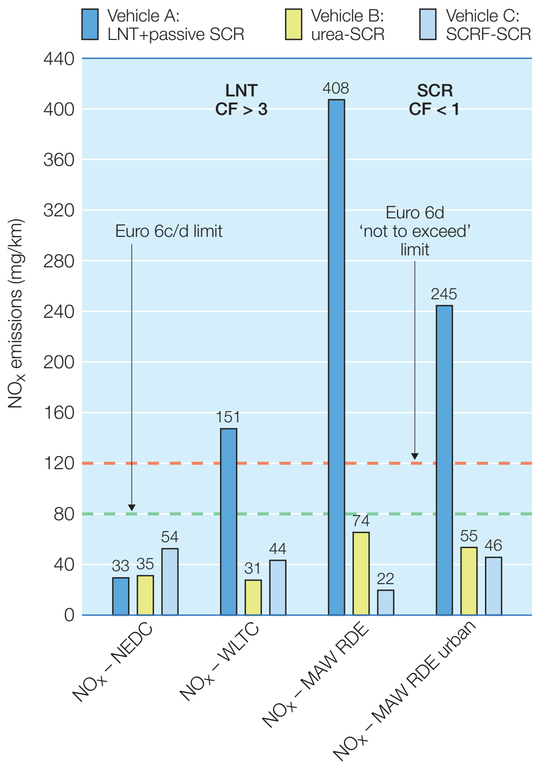
rapid acceleration and speed variability on emissions was also tested but is not discussed here. The NEDC lasts ~20 minutes and covers ~11 km, and the WLTC lasts ~30 minutes and covers ~23 km.

The RDE route used is illustrated in Figure 6a. The route commences with urban operation wholly in 20 and 30 mi/h (32–48 km/h) zones. Rural and motorway phases are conducted on major roads to the west and east of Ricardo's site, respectively. The requirements of the test are achieved without introducing artificial stop periods, and urban severity is achieved through moderate hill climbs and multiple T-junctions. Hill climbs and descents are also present in both rural and motorway sections. The total test time is around 105 minutes and cold start emissions were included in the analysis.

NO_x emissions

For NO_x emissions, two of the vehicles (B and C) gave results well below the Euro 6 limit (shown by the green dotted line on Figure 7), while for vehicle (A) only the NEDC results were below the limit (Figure 7). Vehicles B and C were both equipped with urea-SCR systems and both high and low pressure EGR, and were certified to Euro 6b and Euro 6c respectively. These vehicles used an active urea dosing strategy that responded to engine-out NO_x levels in real time. Vehicle A was a Euro 6b vehicle equipped with a lean NO_x trap (LNT) and passive SCR. NO_x emissions from the LNT-passive SCR car (A) increased with cycle duty and exceeded the Euro 6 limit over the WLTC and during both the urban and total RDE cycles. It is notable that the non-urea-SCR car (A) produces around half of the NO_x in the urban portion of the RDE than it does in the full RDE, whereas vehicle B produces similar NO_x over urban and whole RDE and vehicle C produces higher NO_x over the urban section of the RDE. The urea-SCR

Figure 7 NO_x emissions from vehicles A, B and C under the various test cycles



vehicles (B and C) appear to have the capability of reducing tailpipe NO_x via urea-SCR activity irrespective of the engine-out level, whereas the Euro 6b LNT vehicle was not optimized to handle high engine-out NO_x levels associated with high exhaust gas flow rates and temperatures, which are conditions encountered in non-urban driving. The dominance of high-temperature operation in these cycles limited NO_x storage and reduction via the LNT. The extended heat-up time of the larger catalyst volume in the urea-SCR-only vehicle may explain why vehicle B has lower performance than vehicle C in the urban section.

Three Euro 6 diesel passenger cars with differing exhaust aftertreatment technologies have been tested over the NEDC and WLTC chassis dynamometer test cycles as well as over the RDE test cycle. The test results show that state-of-the-art diesel passenger cars are capable of meeting near future NO_x emissions requirements of moderate RDE testing commensurate with Euro 6d. Combinations of emissions control technologies, for example long- and short-route EGR, large-volume SCR and possibly LNT will be required. Vehicles equipped with urea SCR systems can reduce tailpipe NO_x by reactive urea reductant dosing varying the urea-reductant consumption, and can therefore produce acceptable NO_x emissions even over high-duty drive cycles. Future work will involve investigation of emissions under more severe test cycles and a wider range of temperatures, and will also involve updating the urban air quality study using the results obtained from these studies.

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