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NO_X emissions from heavy-duty and light-duty diesel vehicles in the EU: Comparison of real-world performance and current type-approval requirements

More diesel vehicles are sold in Europe than in China, India, and all of the Americas combined—over 8.8 million in 2014 alone, more than double the sales in the next largest diesel market, China (Figure 1). The majority of the diesels sold in Europe, as in the global market, are passenger cars; approximately five diesel passenger cars were sold worldwide for every heavy-duty vehicle.

The months since the Volkswagen emissions cheating scandal broke in September 2015 have seen a heated public debate concerning exhaust emissions of nitrogen oxides (NO_X) from diesel cars in Europe. The crux of that debate is that under normal operation many of these vehicles far exceed the limits imposed by regulation and certified by official type-approval tests, which all vehicle models must pass as a condition of being offered for sale in the European Union. There has been little comparable discussion of NO_X emissions from diesel trucks. The most likely explanation for this different treatment is that data from in-use testing indicates that, in contrast to Euro 6 cars, Euro VI trucks do not systematically emit significantly more NO_X in real-world, everyday operation than they are certified to.[1] And there is a likely explanation for that as well: emissions from diesel cars and trucks are regulated differently under the Euro standards.

This briefing paper identifies key differences in the regulations governing certification of NO_X emissions from diesel cars (Euro 6) and trucks (Euro VI) that help explain differences in their real-world emissions performance. Ultimately, an examination of the

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[1] European Union heavy-duty engine emission standards are denoted by Roman numerals, while light-duty vehicle standards are denoted by Arabic numerals. Euro 6/VI are the current standards, applying to all new cars and trucks. These standards succeed Euro 1–5 and I–V, which imposed less stringent limits on pollutant emissions and also differed with respect to type approval test protocols.

Prepared by Rachel Muncrief

heavy-duty vehicle regulation reveals insights that could be used to improve the light-duty vehicle regulation.

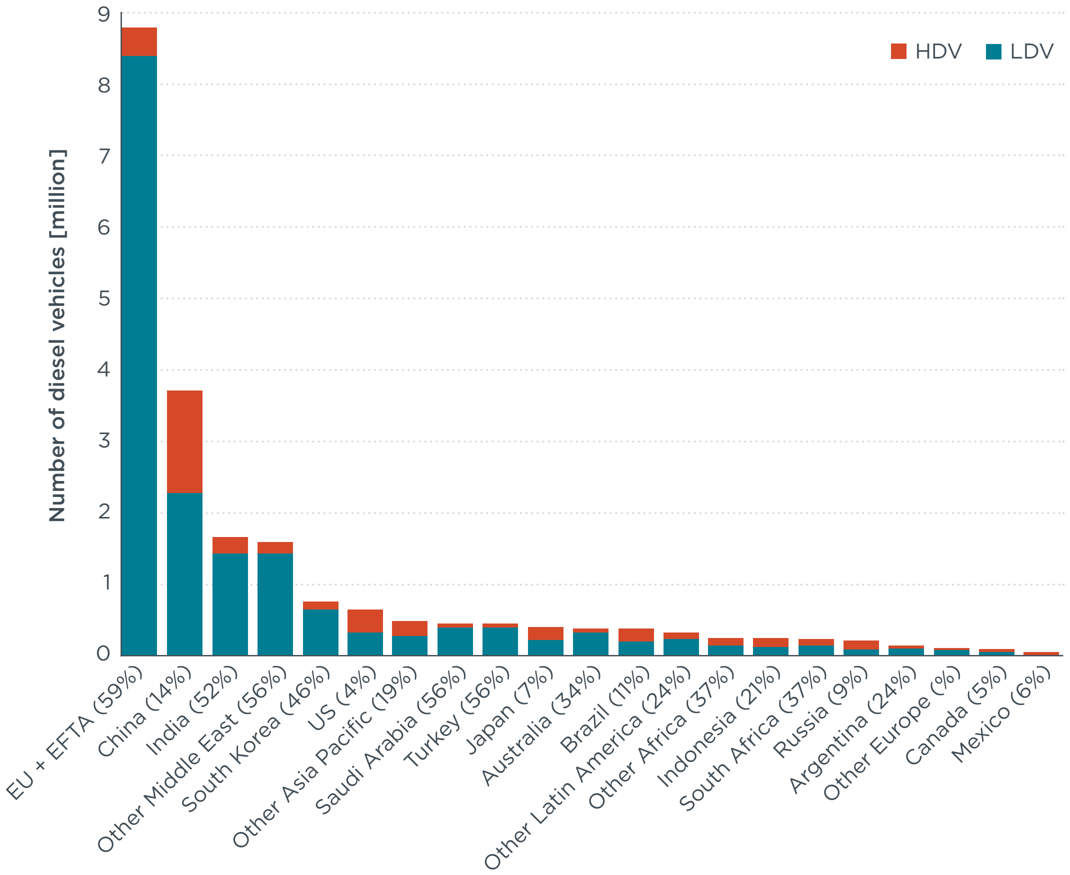

Figure 1. 2014 sales of heavy-duty and light-duty diesel vehicles in various markets. Diesel percentage of new total vehicle sales is shown in parentheses.[2]

CONTROLLING NO_X EMISSIONS FROM DIESEL VEHICLES

There is no significant difference in chemical make-up between the engine exhaust of the smallest diesel car and the engine exhaust of the largest diesel truck. The technologies[3] used to control the pollutants contained in that exhaust are also similar. Most manufacturers use a combination of in-cylinder controls that affect the proportions of pollutant compounds that are left over from combustion and enter the exhaust stream and aftertreatment devices that remove pollutants from the exhaust after it has exited the engine. Table 1 shows the most common NO_X control technologies.

Cooled exhaust-gas recirculation (EGR) is one of the most important technologies for reducing the NO_X emissions exiting the engine and is used in both light-duty and heavy-duty diesel engines. EGR reduces NO_X by recirculating a portion of the engine exhaust back to the combustion chamber, where it is combined with “fresh” intake air. This effectively reduces the oxygen content and increases the water content of the

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[2] Ulises Hernandez, Joshua Miller, *Methodological notes: Global vehicle sales database* (ICCT: Washington DC, 2015). http://www.theicct.org/methodological-notes-global-vehicle-sales-database

[3] HDV: Francisco Posada, Sarah Chambliss, Kate Blumberg, *Costs of Emission Reduction Technologies for Heavy-Duty Diesel Vehicles* (ICCT Washington DC, 2016). http://www.theicct.org/costs-emission-reduction-tech-hdvs; LDV: Francisco Posada, Anup Bandivadekar, John German, *Estimated Cost of Emission Reduction Technologies for LDVs* (ICCT: Washington DC, 2012). http://www.theicct.org/estimated-cost-emission-reduction-technologies-ldvs

combustion air mixture. Using this combustion-air mixture for in-cylinder combustion has the effect of reducing the peak combustion temperature, thereby reducing the amount of thermal NO production during combustion.

The key difference in NO_x emissions control between light-duty and heavy-duty vehicles is that cars can, depending on engine size and other factors, use either a lean NO_x trap (LNT) or selective catalytic reduction (SCR) to control NO_x in the engine exhaust (that is, both are aftertreatment technologies), whereas for a variety of reasons relating to engine size, operating characteristics, and technology costs, as a practical matter heavy-duty vehicles being produced today only utilize SCR systems. A lean NO_x trap uses a catalyst to temporarily store NO_x from the exhaust. At intervals (ranging from seconds to minutes depending on operational conditions), the engine controller must briefly increase the proportion of fuel in the air-fuel mixture being combusted (make it "richer") , which regenerates the catalyst as the stored NO_x reacts with hydrocarbons in the exhaust to produce nitrogen and water. Selective catalytic reduction reduces NO_x to nitrogen over a catalyst using ammonia as the reductant. The ammonia is typically supplied in the form of urea, which must be stored in a tank on the vehicle. LNT is not currently a practical option for trucks because the catalyst uses costly platinum-group metals, and larger engines, with greater displacement and consequently a greater exhaust volume, require larger and therefore more costly catalysts. In addition, HDV fleets can purchase urea in bulk, which can make urea-based SCR systems all the more cost effective. Thus, small LNTs are only more economical than SCR systems for passenger vehicles with engine displacement below 2 liters.[4]

Table 1. In-cylinder and aftertreatment technologies that may be used to meet Euro VI/6 NO_x emissions standards

	HDV	LDV
In-Cylinder		
High-pressure fuel injection	X	X
Variable-geometry turbocharger	X	X
Cooled exhaust-gas recirculation (EGR)	X	X
After-treatment		
Zeolite or Vanadia based SCR catalyst system	X	X
LNT catalyst system		X

While the chemical composition of the exhaust and the emission-control technologies are the same for light-duty and heavy-duty diesel vehicles, the technical challenges related to NO_x control they present do differ in some important particulars. The relative lack of physical space in which to install emissions-control hardware is a key challenge for cars, especially small cars. In the passenger-car market diesels compete with petrol vehicles, which can control NO_x emissions easily and cheaply using a three-way catalyst and do not need additional aftertreatment devices. In contrast, the heavy-duty market is completely dominated by diesel; in the EU more than 99% of new heavy-duty vehicle registrations are diesels. Consequently, the incremental cost of emission controls is a far more important issue for diesel cars than trucks, and the technology required to meet Euro 6 emissions regulations imposes an appreciable cost premium on diesel cars relative to comparable gasoline vehicles.

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[4] Francisco Posada, Anup Bandivadekar, John German, *Estimated Cost of Emission Reduction Technologies for LDVs* (ICCT: Washington DC, 2012). http://www.theicct.org/estimated-cost-emission-reduction-technologies-ldvs

REAL-WORLD NO$_X$ EMISSIONS

Test data on Euro 6 diesel cars published by independent research organizations and EU member state governments alike has shown that, on average, their real-world NO$_X$ emissions are 6 to 7 times the limit of 80 mg/km mandated by the Euro 6 standard.[5] Figure 2 shows a representative example of this data, the results of emissions tests conducted by the German government on 30 Euro 6 vehicles.

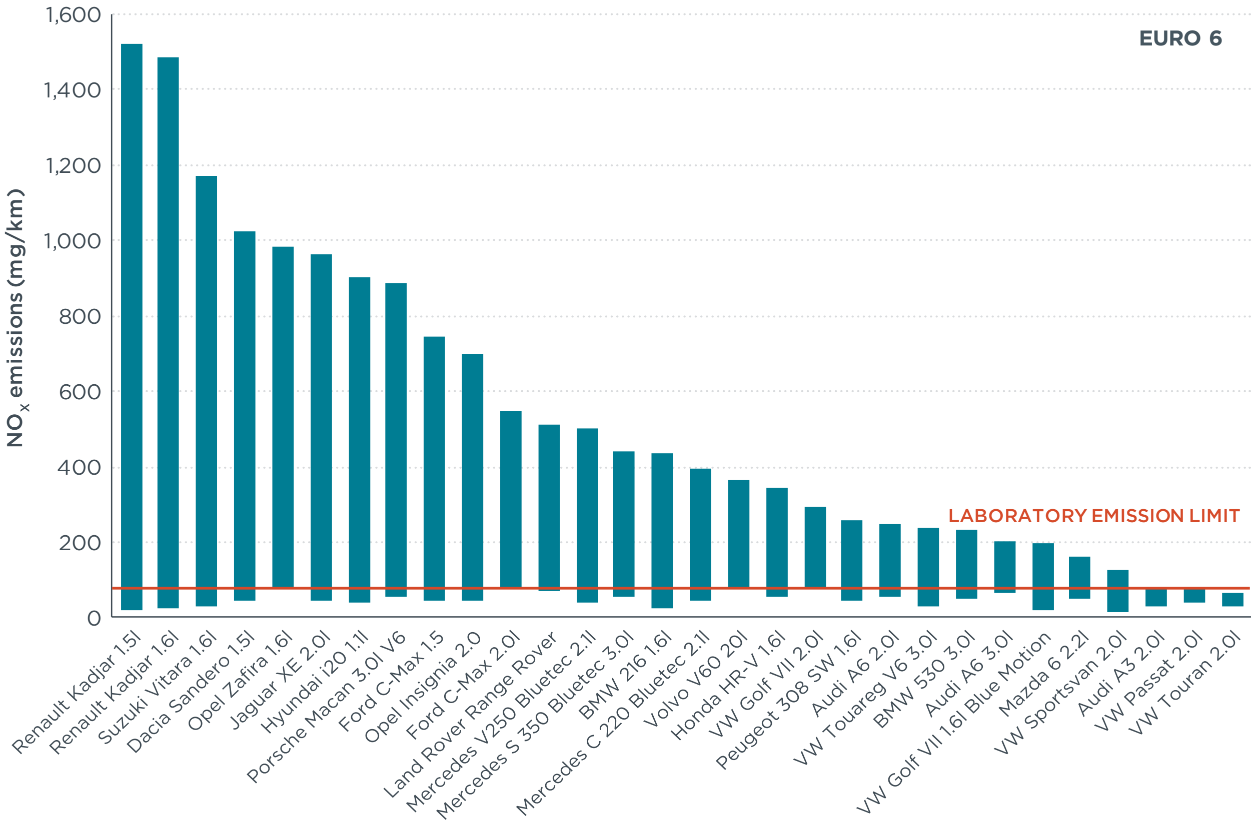

Figure 2. Range of KBA/BMVI test results. Bottom value of each bar corresponds to NEDC laboratory test result, top level of the bar to maximum on-road test result

Little data on real-world emissions from heavy-duty vehicles in Europe has been published.[6] The ICCT has acquired data on real-world emissions for a total of 24 Euro VI vehicles (buses, tractor-trailers, and rigid trucks) from two sources: VTT labs in Finland, which provided chassis-dynamometer testing data, and the German type-approval authority (KBA), which provided PEMS in-service conformity testing data. For illustrative purposes the VTT data is summarized in Table 2.

The average NO$_X$ emissions of the testing data from the 24 heavy-duty vehicles mentioned above was 210 mg/km, less than half the average NO$_X$ emissions from Euro 6 cars (480–560 mg/km) found by both independent measurements and Member State testing. In addition, the average conformity factor[7] was less than 1, meaning that on-road emissions stayed below the Euro VI engine type-approval test limits.[8]

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[5] For detailed summaries of this research, and of the EU member state testing results, see the papers and other materials collected at http://www.theicct.org/spotlight/use-nox-emissions.

[6] Some HDV testing data has previously been published in summary form by a limited number of organizations, including TNO and Transport for London. The data presented in this report represents the complete data sets that ICCT was able to access.

[7] Conformity factor is defined as the ratio of the test result to the regulatory limit.

[8] For the VTT data, emissions results were converted from g/km to g/kWh based on estimation of engine power over the test cycle from the power measured at the dynamometer roll. For the KBA data, values were already supplied in g/kWh and no conversion was necessary.

Table 2. Results of heavy-duty chassis dynamometer emissions testing (VTT labs)

Vehicle number	Type	Number of tests	Avg. speed (km/hr)	Avg. NO_x (g/km)	Avg. CO_2 (g/km)	Fuel consumption (l/100km)	CO_2 / NO_x ratio	Avg. conformity factor
1	Rigid	8	70	0.366	1079	38.8	2950	0.65
2	Tractor	9	72	0.101	827	31.5	8182	0.21
3	Tractor	4	81	0.204	699	26.7	3417	0.49
4	Tractor	6	81	0.014	575	21.2	41219	0.04
5	Bus	4	23	0.311	965	35.7	3101	0.87
6	Bus	6	22	0.021	1325	49.2	61856	0.04
7	Bus	6	22	0.021	1075	40.4	51225	0.05
8	Bus	2	22	0.193	976	36.1	5052	0.51
9	Tractor	6	40	0.108	1073	38.7	9934	0.17
10	Bus	2	22	0.419	1427	52.1	3404	0.71
11	Bus	2	22	0.022	1159	41.7	51844	0.05

Figure 3 shows average real-world NO_x and CO_2 emissions of Euro VI heavy-duty diesel vehicles from these two data sources, and of Euro 6 light-duty diesel vehicles as measured by EU Member State tests and independent researchers. On average, NO_x emissions from diesel cars are more than double those of diesel trucks on a per-kilometer basis, even though CO_2 emissions—which are proportional to fuel consumption—for heavy-duty vehicles are five times those of cars. That is, on an engine-load basis, heavy-duty diesel vehicles are roughly ten times better than light-duty diesels at reducing NO_x emissions. This indicates that tailpipe NO_x emissions have been essentially decoupled from CO_2 emissions, so that increases in CO_2 emissions—that is, in fuel consumption—do not necessarily produce an increase in NO_x emissions. (Heavy-duty vehicles are typically driven further every year than light-duty vehicles, so this data does not imply anything about total annual emissions per vehicle type.)

The data indicates that proper (meaning in compliance with mandated limits) real-world control of NO_x is technically possible. It is also worth noting that significant real-world emissions reductions (and conformity-factor reductions) were accomplished in the transition from Euro V to Euro VI HDV standards. Available testing data shows that Euro V conformity factors were as high as 4.8, which is a level of noncompliance comparable to that of light-duty Euro 5 vehicles. The highest conformity factor observed in Euro VI testing results is 1.7.

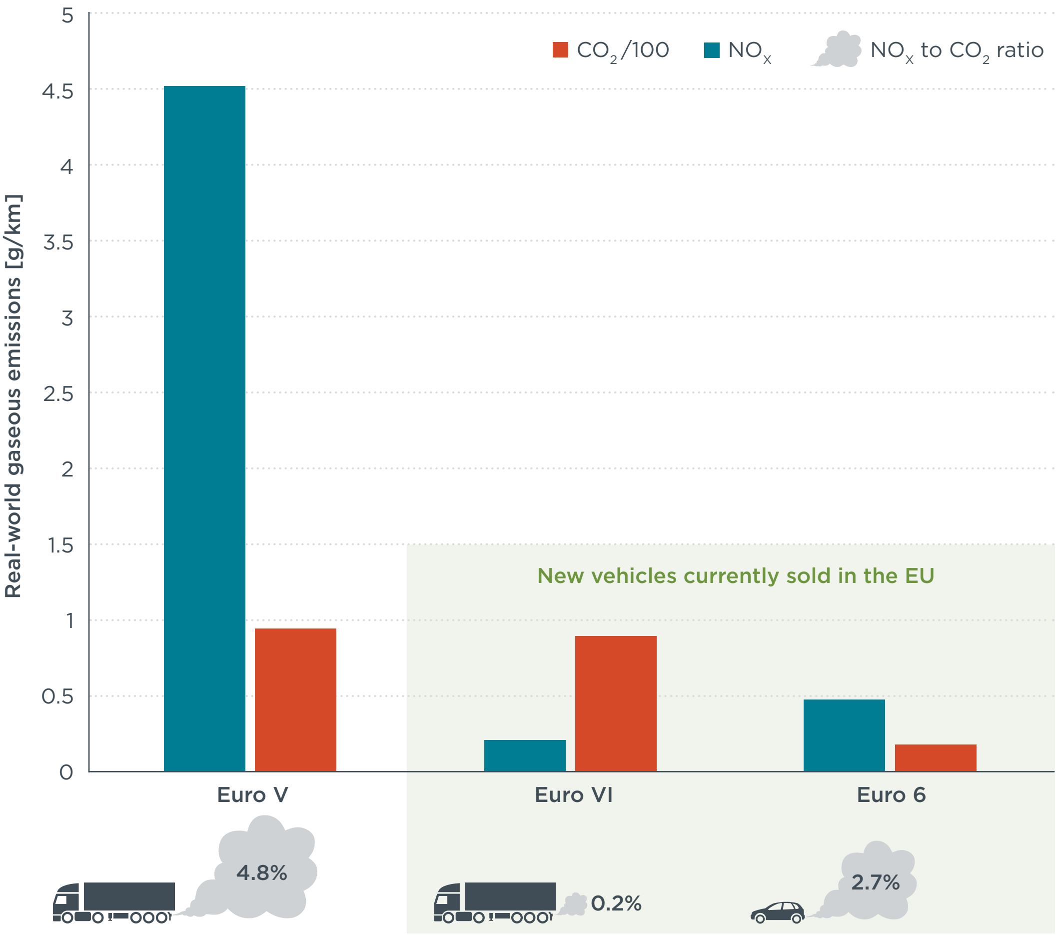

Figure 3. Average real world NO_x and CO_2 emissions of Euro V/VI/6 heavy-duty and light-duty vehicles.

COMPARISON OF LDV AND HDV TYPE-APPROVAL REQUIREMENTS

The European Union has mandated significant reductions in NO_x tailpipe emissions from both heavy-duty diesel engines and diesel passenger vehicles since 2000: 91% for heavy-duty engines, 84% for diesel passenger vehicles. Table 3 shows the timeline for implementation and the emissions limits of the succession of standards adopted over that period. In general, the timelines have followed similar schedules from Euro III/3 through Euro VI/6, with implementation of the heavy-duty standard leading light-duty by a year in most cases. It is difficult to compare the light-duty and heavy-duty emissions limits directly because the type-approval test for heavy-duty engines is conducted on an engine dynamometer and the emission limits are defined in terms of mass emitted per unit of mechanical work done (g/kWh), while the type-approval test for passenger vehicles is performed on a chassis dynamometer and the emission limits are defined in terms of mass emitted per unit of distance driven (g/km).

Table 3. Timeline of Euro regulations for heavy-duty engines and passenger vehicles

	Heavy-duty engine (engine dynamometer test)			Passenger vehicle (chassis dynamometer test)		
Euro level	**NO_x emissions limit**	**% reduction from previous regulation**	**Year of implementation (mandatory for new type-approvals)**	**NO_x emissions limit**	**% reduction from previous regulation**	**Year of implementation (mandatory for new type-approvals)**
3/III	5 g/kWh		2000	0.5 g/km		2001
4/IV	3.5 g/kWh	30%	2005	0.25 g/km	50%	2006
5/V	2 g/kWh	43%	2008	0.18 g/km	28%	2011
6/VI	0.4/0.46 g/kWh	77%-80%	2014	0.08 g/km	56%	2015

As discussed above, data indicates that real-world NO_x emissions from light-duty Euro 6 diesel vehicles in everyday operation routinely fail to comply with the emissions limits defined in the Euro 6 regulation. European Union regulators have been working to improve that regulation. Two significant changes to the passenger vehicle emissions type-approval test protocol will be phased in beginning in 2017. The recently finalized Real Driving Emissions (RDE) test protocol, a supplemental type-approval test which measures emissions during on-road driving within defined boundary conditions, will be required for new vehicle types in September 2017, and will be fully phased in for all new registrations by September 2019.[9] And a new chassis dynamometer test protocol, the Worldwide Harmonized Light Vehicles Test Procedure (WLTP), will begin to phase in with model year 2017 vehicles. Changes with the WLTP include most importantly a new process for determining road-load coefficients used to set up the chassis dynamometer and a new dynamometer driving cycle that is more representative of actual driving conditions than the current cycle (the New European Driving Cycle, NEDC).[10]

Additional changes to the light-duty vehicle test protocol that are not yet finalized include adding cold-start testing to the RDE test protocol and mandating in-service conformity testing using PEMS[11].

EMISSIONS TYPE-APPROVAL TEST

The type-approval test is an important element of a vehicle emissions regulation, and a well-designed type-approval test can have significant influence on real-world emissions over life of the vehicle.[12]

Emissions type approval for a heavy-duty engine or light-duty vehicle in the EU may be granted by any one of 28 national type-approval authorities.[13] A manufacturer must receive full type approval (emissions type approval is only one part of the vehicle certification process) on a pre-production engine or vehicle before it may be mass

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[9] EC, European Commission. Commission Regulation (EU) 2016/427 of 10 March 2016 amending Regulation (EC) No 692/2008 as regards emissions from light passenger and commercial vehicles (Euro 6); 2016; EC, European Commission. Commission Regulation (EU) 2016/646 of 20 April 2016 amending Regulation (EC) No 692/2008 as regards emissions from light passenger and commercial vehicles (Euro 6); 2016.

[10] European Commission Daily News, "Car emissions: EU moves closer to more robust testing methods for CO2 emissions and fuel consumption," June 15, 2016, http://europa.eu/rapid/press-release_MEX-16-2223_de.htm

[11] Cold-start testing is included in RDE package 3, proposed in November 2016, and in-service RDE testing will be included in package 4 (proposal date not confirmed). RDE package 3 proposal can be found here: https://ec.europa.eu/info/law/better-regulation/initiatives/ares-2016-6339064_en

[12] Note that the type-approval test is only one of several important elements of an emissions regulation; others include in-use surveillance testing requirements, durability requirements, on-board diagnostics (OBD) requirements, and enforcement provisions, including the ability to levy fines or force recalls. But even a cursory discussion of those aspects of a vehicle emissions regulation is beyond the scope of this briefing.

[13] Information about the European type-approval process can be found here: http://ec.europa.eu/growth/sectors/automotive/technical-harmonisation/eu/index_en.htm

produced and sold. To obtain an emissions type approval a manufacturer first arranges to have a vehicle or engine tested by an independent third party.[14] Called technical services, these third parties are approved laboratories that have the equipment and expertise to perform testing as defined in the regulation.[15]

The type-approval tests that passenger vehicles and heavy-duty engines must pass are very different. Some of the key differences that begin to help explain the differences in real world emissions between heavy-duty and light-duty vehicles are laid out in Table 4, which compares elements of the type-approval test protocols for Euro IV/V (past), Euro VI (current), Euro 6 (current), and future Euro 6 (with the addition of WLTP and RDE).

Table 4. Comparison of various heavy-duty and light-duty type-approval tests

	Euro IV/V (past)	Euro VI (current)	Euro 6 (current)	Future Euro 6 (WLTP/RDE)	
Test type	Engine dynamometer	Engine dynamometer	Chassis dynamometer	Chassis dynamometer	PEMS
Duty Cycle(s)	European Steady-State Cycle, ESC (steady state), European Transient Cycle, ETC (transient)	World Harmonized Steady-State Cycle, WHSC (steady state, hot-start test only), World Harmonized Transient Cycle, WHTC (transient, cold- and hot-start test)	NEDC (transient, cold-start test)	WLTC (transient, cold-start test)	RDE test cycle on the road (combination of urban, rural, motorway driving—33% each—distance-based)
Idling time	6% (of total ETC time)	17% (of total WHTC time)	23.7% (of total NEDC time)	12.6% (of total WLTC time)	6%–30% (of urban driving)
Average engine load	55% (ESC) 31% (ETC)	25% (WHSC), 17% (WHTC)	N/A	N/A	N/A
Average vehicle speed	N/A	N/A	33.6 km/h	46.5 km/h	Urban (15–40 km/h, rural (60–90 km/h), motorway (over 90 km/h)
% constant speed driving	Two separate test cycles, one steady state (speed/load), one transient. Each have to meet the emissions limit	Two separate test cycles, one steady state (speed/load), one transient. Each have to meet the emissions limit	40.3%	3.7%	
Cold-start test	No	Yes. Weighting is 14% (WHTC only)	NEDC is a cold-start test	WLTC is a cold-start test	Proposed[16]
Off-cycle test[17]	No	Yes (0.6 g/kWh NO_x limit) – World Harmonized Off-Cycle Emissions (OCE) test.	No	No	RDE could be considered an off-cycle test

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[14] The technical services must compete with each other for manufacturers' business, which raises a concern with regard to their impartiality. A European Commission proposal is currently on the table that would break the financial link between the OEMs and technical services.

[15] It is currently permissible under European law that a representative from a technical service may observe a test being conducted at a manufacturer-run laboratory, rather than conduct the test themselves.

[16] Cold-start testing under RDE will be phased in starting in September 2017 if the RDE package 3 proposal is approved as written.

[17] An off-cycle test is a test that measures emissions from the engine at points outside of the prescribed type-approval test cycle

A robust emissions type-approval test should ensure that emissions-control systems operate effectively over a wide range of conditions, such as when exhaust temperatures are both high and low, during transient engine operation, under high engine load, and with a high exhaust flow rate. A known deficiency of Euro IV/V heavy-duty vehicles is that they have extremely high NO_X emissions in urban driving conditions.[18] As Table 4 shows, the Euro IV/V type-approval test did not have the engine operate for any significant amount of time in low-engine-load or low-exhaust-temperature conditions. Therefore, manufacturers did not need to engineer the emissions control system to work effectively under those conditions in order to pass the test. This feature of the test protocol is likely to have had a major impact in the real-world performance characteristics of Euro IV/V vehicles. Euro VI improved the situation by adding a cold-start test and using a new test cycle with lower engine loads and increased time idling. The data shows that Euro VI vehicles do indeed have significantly lower urban NO_X emissions that Euro IV/V vehicles.[19]

The current Euro 6 light-duty vehicle test protocol does include a significant amount of low-engine-load, idling, and low-exhaust-temperature operation, but it is lacking in other areas. It does not include a significant amount of time operating at high engine load and high exhaust temperature, nor does it include much transient operation (due to the stylized, geometric speed-time drive trace of the NEDC test cycle). This may partially explain high real-world NO_X emissions in these driving situations, although clearly a major cause of high real-world NO_X emissions from passenger cars is manufacturers' use of defeat devices to circumvent the type-approval test.[20] The WLTC features more transient operation, and the test cycle will generate higher engine loads and exhaust temperatures than the NEDC.

Another important change with the adoption of Euro VI was the addition of a so-called off-cycle test to the heavy-duty engine type-approval process. Additional randomly selected points on the engine map—that is, engine-speed versus torque or load combinations—falling outside the test cycle but within a specified range, are tested to ensure that the emissions-control system is not narrowly calibrated to meet emissions limits while being operated on the test cycle but then exceed the limits (for example, in order to improve a trade-off in fuel consumption) as soon as the engine is being operated off the type-approval test cycle. Since the manufacturer cannot know ahead of time the random off-cycle test points, the engine emissions control system must be designed to function over a large part of the engine map.

The current Euro 6 type-approval test for passenger cars does not include an off-cycle test, which means that vehicles are only required to demonstrate emissions compliance at the exact engine-speed/load points that occur as the vehicle is operated on the chassis dynamometer over the drive cycle specified for the NEDC test. The addition of the RDE test to the light-duty vehicle type-approval process will effectively introduce off-cycle testing for light-duty vehicles and should therefore reduce the discrepancy between type-approval and real-world emissions.

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[18] Dana Lowell and Fanta Kamakaté, *Urban Off-Cycle Emissions from Euro IV/V Trucks and Buses* (ICCT: Washington DC, 2012). http://www.theicct.org/urban-cycle-nox-emissions-euro-ivv-trucks-and-buses

[19] Rachel Muncrief, *Comparing Real-World Off-Cycle NO_X Emissions Control in Euro IV, V, and VI* (ICCT: Washington DC, 2015). http://www.theicct.org/comparing-real-world-nox-euro-iv-v-vi-mar2015

[20] Rachel Muncrief, John German, and Joe Schultz, *Defeat Devices Under the U.S. and EU Passenger Vehicle Emissions Testing Regulations* (ICCT: Washington DC, 2016), http://www.theicct.org/briefing-defeat-devices-us-eu-vehicle-emissions-regulations

ON-ROAD AND IN-USE TESTING

Portable emissions measurement systems (PEMS), which can measure exhaust emissions during on-road driving, have been used to confirm whether heavy-duty engines continue to comply with the emissions standards while in use—that is, in normal operation, over time, under real-world conditions—since Euro VI came into effect.[21] This is known as in-service conformity (ISC) testing. The Euro 6 regulation also includes ISC testing, but the test protocol is typically a duplication of the original type-approval test, rather than an on-road test. Table 5 summarizes elements of the ISC testing for Euro VI and 6.

Table 5. In-service conformity requirements for Euro VI and 6

	Euro VI (current)	Euro 6 (current)
Test description	Mix of on-road urban, rural, motorway driving (no cold start). Emissions measured with PEMS.	NEDC dynamometer test
Sample size	3 engines per family (minimum), defined statistically[22]	3 vehicles per family (minimum)
Sample selection	Selected by manufacturer and approved by type-approval authority	Defined by manufacturer (must be selected from at least two member states)
Test frequency	First test at 18 months after sale and after a minimum of 25,0000 km driven and then every two years	First test at 15,000 km driven after sale or 6 months, whichever occurs later, then every 18 months
Lifetime coverage of testing	700,000 km or seven years, whichever is sooner (for 16+ ton)	100,000 km or 5 years, whichever is sooner

On-road PEMS testing, in the form of the RDE test, will be mandatory for all new passenger vehicles beginning in September 2019. The RDE test, as presently defined, only covers pre-production vehicles and is not required for in-use vehicles. This is in contrast to the regulatory requirement for ISC testing of heavy-duty engines. In other words, PEMS testing is used in different ways under Euro VI (for in-service conformity testing, during the lifetime of the vehicle) and Euro 6 (for pre-production type-approval testing).

Table 6 summarizes the elements of the PEMS test protocols for HDVs and LDVs. There are a number of similarities and differences between the two tests that may ultimately have an impact on real-world emissions. In both, the vehicle is driven in urban, rural, and motorway conditions. The speeds are lower for the heavy-duty vehicle, which reflects actual practice; trucks drive at slightly lower average speeds than cars on the road. Neither test currently requires that emissions during the cold start be measured, meaning that pollutants emitted as the engine and catalyst warm up to operating temperature are not currently included in any PEMS test calculation. Cold-start NO_x emissions are known to be technically challenging to control. Cold-start emissions are included in LDV and HDV type-approval dynamometer tests, so although cold-start evaluation is not currently part of PEMS testing it is evaluated at type approval. The inclusion of cold-start emissions during PEMS testing has been

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[21] EC, European Commission. Commission Regulation (EU) No 582/2011 of 25 May 2011 implementing and amending Regulation (EC) No 595/2009 of the European Parliament and of the Council with respect to emissions from heavy duty vehicles (Euro VI) and amending Annexes I and III to Directive 2007/46/EC of the European Parliament and of the Council; 2011; EC, European Commission. Commission Regulation (EU) No 64/2012 of 23 January 2012 amending Regulation (EU) No 582/2011 implementing and amending Regulation (EC) No 595/2009 of the European Parliament and of the Council with respect to emissions from heavy duty vehicles (Euro VI); 2012.

[22] With a minimum sample size of three engines the sampling procedure shall be set so that the probability of a lot passing a test with 20% of the vehicles or engines defective is 0.90 (producer's risk = 10%) while the probability of a lot being accepted with 60% of the vehicles or engines defective is 0.10 (consumer's risk = 10%).

proposed for light-duty vehicles to start in September 2017 and is currently being considered for heavy-duty vehicles.

Both Euro VI and the RDE test regulation define a conformity factor, or not-to-exceed multiplier, for on-road emissions. The NO_x conformity factor for in-use heavy-duty engines is 1.5—that is, NO_x emissions measured during an on-road test of an in-use engine using PEMS equipment may not be more than 1.5 times the Euro VI NO_x emissions limit—whereas the initial RDE conformity factor for passenger vehicles is 2.1 (with plans to eventually go to 1.5). This is a significant difference, considering that the passenger vehicle test is for pre-production vehicles only and the heavy-duty test is for vehicles that have been in operation for as long as seven years or 700,000 kilometers. In addition, as discussed above, the RDE test is essentially being used as an off-cycle type approval test. The current heavy-duty engine off-cycle test requires a conformity factor of around 1.5.

Requirements concerning ambient temperature and barometric pressure also differ for the heavy-duty and light-duty tests. Heavy-duty vehicles can be tested in temperatures as low as -2 °C, but passenger vehicles are to be primarily tested at 3 °C and above (although, as noted in Table 6, there are certain provisions that increase the allowable emissions during the test if a vehicle is tested at temperatures below 3 °C). In addition, the barometric pressure (or given altitude) range is also wider for heavy-duty vehicle PEMS testing (1700 meters for heavy-duty and only 700 meters for light-duty).[23] As noted above, the NO_x emissions-control technology used in light-duty and heavy-duty vehicles is similar. There is no technical reason why a light-duty vehicle's emissions-control system should not be effective over the same temperature and barometric pressure ranges as a heavy-duty emissions-control system.

In addition to these restrictions placed on on-road tests that influence when and under what conditions emissions are measured, some of the data collected during testing are excluded before the final emissions value for the test is calculated. This is done according to rules summarized in the last two rows of Table 6. The calculation rules differ for the two PEMS tests. For heavy-duty vehicle testing, the emissions data is integrated over a series of "work-based windows." The size of each window is equivalent to the total work done by the engine during the transient engine type-approval test (WHTC). The average emissions conformity factor from each window is determined. A given window may be thrown out if the average engine power is too low (20% of maximum power). The final and official conformity factor resulting from the test is the result at the 90th percentile of all the valid windows.

The prescribed RDE data evaluation methods use either distance-specific CO_2 emissions over the windows (moving averaging window method) or instantaneous power at the wheels (power-binning method) to verify the normality (as defined by the CO_2 emissions or power measured during the WLTC dynamometer test) of driving conditions and apply corrections to the measured signals. These corrections may shift the reported emissions up or down with respect to the "raw" measured emissions. Neither method explicitly excludes individual data points (apart from the cold-start section, which, as previously mentioned, will be covered in the third legislative package of RDE), but they apply lower weightings to data windows or bins with unusually low or high CO_2 emissions or average power. The resulting driving style that is implicitly prescribed during the data evaluation (results post-processing step) is close to the driving style that characterizes the drive cycle of the WLTP test (i.e., mild, non-aggressive driving).

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[23] The testing altitude can go as high as 1300 meters, but these are considered "extended" testing conditions, in which a special emissions allowance applies.

Table 6. Comparison of Euro VI and Euro 6 on road testing procedures

	Euro VI	Euro 6 (future)
PEMS testing program	In-service conformity (ISC)	Real-driving emissions (RDE)[24]
Implementation year	2014	2017 (first step, conformity factor of 2.1)
Analytical equipment	PEMS	PEMS
Vehicles tested	In-use	Pre-production[25]
Applicable vehicles	M1/M2/M3; N1/N2/N3 over 2,610kg	M1, N1, N2[26]
Mandated test frequency	18 months with minimum of 25,0000km and then every two years	Once at type-approval
Driving shares (% of distance)	Urban (0–50 km/h; 20%–45%) Rural (50–75 km/h; 25%–30%) Motorway (75 km/h+; 30%–55%)	Urban (0–60 km/h; 29%–44%) Rural (60–90km/h; 23%–43%) Motorway (90km/h+; 23%–43%)
Sample size	3 engines per engine family	1 representative vehicle of the “PEMS test family”
Cold start included	No[27] (analysis starts when coolant temp >70°C, when engine coolant is stabilized within +/-2K, or 20 minutes whichever is first)	Current regulation states analysis starts when coolant temp >70 °C or 5 minutes, whichever is first. Currently proposed regulation includes analysis of cold-start data
NO_x Conformity factor	1.5	2.1 (between 2017 and 2020), 1.5 (after 2020)
Test length	Defined by WHTC work (5x work of WHTC)	90 to 120 minutes
Payload	50%–60%	2 test operators plus the test equipment, Up to 90% of maximum permissible payload
Vehicle Preparation	OBD check, replace oil, fuel, reagent	General technical and operational check
Vehicle Driver	Usual professional driver of the vehicle	Driver supplied by manufacturer or technical service
Ambient conditions	Atmospheric pressure ≥ 82.5 kPa (altitude of approximately 1700 m), Temperature ≥ -7°C, Temperature ≤ 37.85 °C (at atmospheric pressure of 101.3 kPa)[28]	Altitude ≤ 700m. Temperature ≥ 3 °C, Temperature ≤ 30 °C. For “extended” ambient conditions of altitude between 700–1300m and temperatures between -7°C to 3°C and 30 to 35 °C emission during this time interval are divided by 1.6

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[24] The term “real driving emissions” could lead people to believe that the results actually represent “real world driving”—which they do not. There is a distinction between “RDE” testing and “real-world” testing. The procedures summarized in Table 6 of this paper refer to RDE testing. True real world emissions evaluation would cover emissions over the full range of vehicle operation, including all ambient conditions and driving patterns.

[25] The RDE tests provide a presumption of conformity at type approval and during the lifetime of a vehicle. The presumed conformity may be reassessed by additional RDE tests.

[26] Implementation dates vary for different vehicle classes

[27] A new proposal from the European Commission to assess the inclusion of cold start emissions in the HDV In-Service Conformity Test can be found here: http://ec.europa.eu/transparency/regcomitology/index.cfm?do=search.documentdetail documentdetail&iL5czRn9Qv8J+RLJlBNqb4MCmQ8l+MR53lPkUjO37gUXV3U4/r7rgJvJWdYwELHg

[28] Equation to calculate maximum temperature is T = - 0,4514 × (101,3 - pb) + 311 (T is the ambient air temperature, K; pb is the atmospheric pressure, kPa)

Table 6. Comparison of Euro VI and Euro 6 on road testing procedures

	Euro VI	Euro 6 (future)
Data analysis	Work-based method: emissions integrated using a moving average window method based on reference work (equivalent to work measured over WHTC). Windows must be validated as to be included in the emissions calculation (50% of the windows must be valid). Conformity factor determined at 90th cumulative percentile of valid emissions data.	CO_2-based method:[29] emissions integrated using a moving average window method (equivalent to CO_2 measured over the dynamometer test cycle). Windows must be validated to be included in the emissions calculation (only "normal" windows are included in the emissions). Conformity factor determined over a trip with a balanced share of urban, rural and motorway driving.
Additional conditions	Power threshold: For a window to be valid, the average power of the window shall be greater than 15-20% of the maximum engine power.[30]	Dynamic conditions: For a window to be valid, the CO_2 for a given average speed must be similar to what it is on the dynamometer test.[31]

Neither the Euro VI nor the Euro 6 protocols correct NO_x for ambient temperature and humidity. Increased water content in the combustion air can have a significant effect on engine-out (i.e., at the entry point to the exhaust system, before any aftertreatment devices) NO_x emissions. The water acts to cool the peak combustion temperature, which can effectively lower engine-out NO_x by over 20%. Therefore, it is possible to find significant reductions in engine-out NO_x emissions when testing on hot and humid days.

SUMMARY/CONCLUSIONS

The best available data shows that the introduction of Euro VI standards significantly reduced real-world NO_x emissions from heavy-duty vehicles. Significant changes between Euro IV/V and Euro VI that likely contributed to that improvement include:

1. Addition of an off-cycle test during type approval
2. Improved type-approval test cycle that includes cold start and lower load conditions as well as transient and high-load conditions.
3. PEMS test for in-service conformity testing, with limited restrictions on the boundary conditions used during the test and subsequent data processing

In its current form, the Euro 6 regulation for diesel passenger cars makes none of the three changes (aside from cold-start and lower-load conditions), which is likely contributing to the high in-use emissions of these cars. The current Euro 6 regulation does not include transient or high-load test, does not include an off-cycle test, and does not include a PEMS in-service conformity test.

Future Euro 6 regulations will incorporate some of these elements through the addition of WLTP and RDE. The WLTP will add a more transient duty cycle with higher load points. RDE will add an off-cycle type approval test using PEMS (and ideally this

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[29] The CO_2 based method was developed by the European Commission's Joint Research Centre. There is an alternative method called the power-binning method (developed by scientists at the Technical University of Graz) that looks at the distribution of power over the test to ensure that the test is comparable to the power distribution driven on the dynamometer test.

[30] Power threshold to be reduced to 10% for new types in 2018 and all vehicles in 2019.

[31] The primary tolerance is ± 25% and the secondary tolerance is ± 50%. The test shall be normal when at least 50% of the urban, rural and motorway windows are within the primary tolerance.

would be extended to in-service conformity testing as well, although the timing is still uncertain). Notably, the current form of the RDE test has boundary conditions that are more restrictive than those of the Euro VI PEMS test.

Although RDE effectively raises the allowable emission limit via a high initial conformity factor, introducing the test will likely cause manufacturers to change the way that NO_x emission aftertreatment systems are calibrated, and therefore RDE should force moderate real-world NO_x emissions performance improvements even in the short term. It should follow that "future Euro 6," including both WLTP and RDE, will result in even lower in-use NO_x emissions from diesel passenger cars. However the first phase of RDE will not be phased in for all new vehicles until 2019, and WLTP will not be fully phased in until 2018. In the meantime, high excess in-use NO_x emissions from diesel cars are likely to continue. Even in 2019, the future Euro 6 (RDE/WLTP) regulation will not be as stringent as the current Euro VI HDV regulation. And if only pre-production vehicles are put through the RDE test, as is the current proposal, it would still be technically possibile for a manufacturer to change the emission-control system calibration for production vehicles to generate much higher in-use NO_x emissions. In view of these risks, the inclusion of RDE into the Euro 6 in-service conformity test protocol should be expedited.