OCTOBER 2019

THE INTERNATIONAL COUNCIL
ON CLEAN TRANSPORTATION

RECOMMENDATIONS FOR POST-EURO 6 STANDARDS FOR LIGHT-DUTY VEHICLES IN THE EUROPEAN UNION

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EXECUTIVE SUMMARY

The European Commission has started the regulatory work aimed at the next stage of emission standards. Post-Euro 6 standards are expected to continue to improve the emissions performance of new road vehicles, addressing their contribution to the persistent air quality issues across Europe. The objective of this paper is to highlight issues and limitations of the current standards, compare them to current and future regulations in other parts of the world, and offer policy recommendations. In the following pages, ICCT makes the following recommendations, summarized in Table 1, on the different topics that should be considered for the light-duty post-Euro 6 standards.

Table 1. Summary of recommendations for post-Euro 6 standards

What to regulate	
Limits	• Introduce fuel- and technology-neutral emission limits • Tighten the emission limits to harmonize with other markets • Introduce application-neutral emission limits
Ultrafine particles	• Lower the size cutoff for particle counting from 23 nm to at least 10 nm • Develop a methodology to measure volatile and semi-volatile particles • Include emissions that occur during filter regeneration • Make particulate number (PN) standards fuel- and technology-neutral • Investigate the feasibility of PN tailpipe measurements
Unregulated pollutants	• Set limits for ammonia emissions • Set limits for CH_4 and N_2O emissions and account for them in the CO_2 standards • Set limits for aldehyde emissions • Regulate all VOCs and not just HC. • Set emission limits for brake wear particles • Consider limits for NO_2 emissions

How to regulate it	
Evaporative emissions	• Tighten the evaporative emissions limit • Introduce an on-board refueling emissions standard • Increase the temperature during hot-soak, prior to the 2-day diurnal test • Introduce requirements for leak monitoring in on-board diagnostics (OBD) provisions
Low temperature test	• Low temperature emission limits should be technology-neutral • Set low temperature limits for a wider set of pollutants • Tighten the current low temperature limits • Develop a new low temperature test procedure • Monitor the greenhouse gas emissions over the low temperature test
On-road CO	• Introduce not-to-exceed limits for CO during real driving emissions (RDE) testing • Reduce the laboratory limit for CO • Introduce limitations for fuel enrichment as an auxiliary emissions strategy
Real Driving Emissions test	• Extend the upper boundary condition for RDE driving dynamics • Eliminate the lower boundary condition for RDE driving dynamics • Revise the vehicle speed requirements during RDE tests • Extend the cumulative elevation gain boundary condition • Extend the temperature range for RDE testing and revise the correction factors • Adjust trip requirements to allow shorter urban sections and cold-start driving • Remove boundary conditions that reveal that an RDE test is taking place • Eliminate the RDE evaluation factor for adjusting emissions downward

	How to guarantee it
Durability	• Extend the definition of useful life for durability demonstration • Establish the whole-vehicle test as the only durability demonstration option • Extend the age/mileage requirements for in-service conformity to the full useful life • Set a minimum emission warranty program • Set an emission defect tracking and reporting program • Develop in-service conformity testing for CO_2, fuel consumption, and electric range • Develop a battery durability test
OBD and OBM	• Align on-board diagnostics (OBD) requirements with those of California and China • Introduce on-board monitoring (OBM) of pollutant emissions • Set OBD threshold limits for PN and reduce the threshold limits for other pollutants • Strengthen the anti-tampering provisions
Market surveillance	• Develop a methodology for fleet screening to identify noncompliant vehicle models • Develop a remote sensing standard and establish a database of measurements • Clarify the criteria for failure of market surveillance tests • Issue defeat device guidance • Extend the scope of market surveillance beyond pollutant emissions

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POLICY BACKGROUND

Air pollution is the leading environmental cause of premature death in the European Union (EU), responsible for more than 400,000 premature deaths per year.[1] According to the World Health Organization (WHO),[2] exposure to air pollution can cause or aggravate heart and respiratory ailments, such as heart attacks and asthma; can affect the nervous and reproductive systems; and has been linked to occurrences of cancer, stroke, diabetes, and Alzheimer's disease.

Despite policymakers' efforts in past decades, approximately one eighth of the EU's urban population is exposed to air pollutant levels exceeding the EU air quality standards. What is more, relative to the more stringent air quality guidelines (AQGs) from WHO, almost all EU citizens living in urban areas are exposed to levels of some air pollutants that are deemed harmful.[3] Figure 1 shows the share of Europe's urban population exposed to particulate matter ($PM_{2.5}$ and PM_{10}), ozone (O_3), and nitrogen dioxide (NO_2) levels above WHO's AQGs. The latter are currently being revised to include the latest evidence on the health effects of air pollutants.[4]

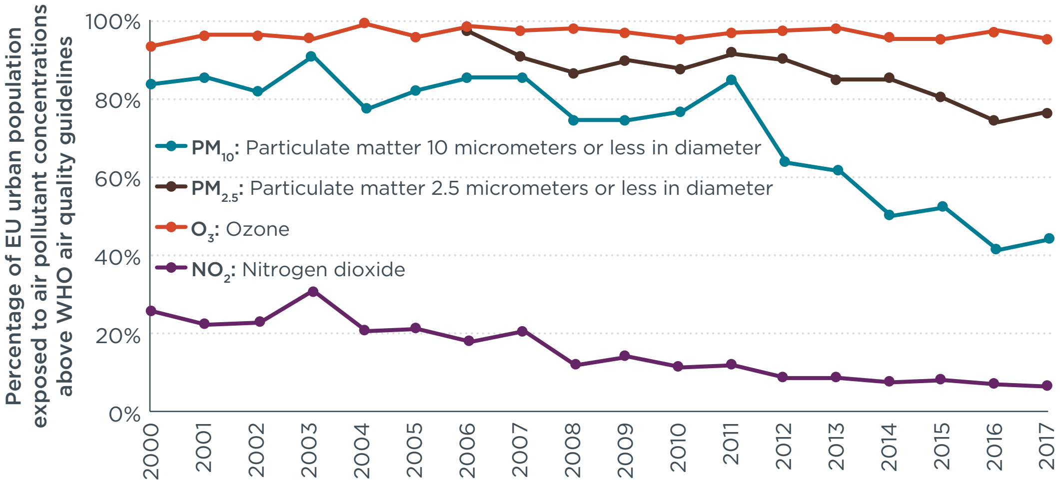

Figure 1. EU urban population exposed to air pollutant concentrations above WHO air quality guidelines from 2000 to 2017 according to the European Environment Agency (2019).

Motor vehicle emissions and their link to air pollution have been recognized as a serious issue since the 1950s, when the link between combustion emissions and photochemical smog was established.[5] Emissions of carbon monoxide (CO), unburned hydrocarbons (HC), nitrogen oxides (NO_x), and particulates are therefore not only concerning because of the health effects associated with direct exposure to them, but also, and more importantly, because of their role as precursors for the formation of $PM_{2.5}$ and ozone in the atmosphere.

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[1] European Environment Agency, *Air quality in Europe — 2018 Report*, (EEA Report No 12/2018, 2018), https://www.eea.europa.eu//publications/air-quality-in-europe-2018.

[2] World Health Organization, *Ambient air pollution: A global assessment of exposure and burden of disease*, (2016), http://www.who.int/phe/publications/air-pollution-global-assessment/en/.

[3] European Environment Agency. "Exceedance of air quality standards in urban areas," (July 3, 2019), https://www.eea.europa.eu/data-and-maps/indicators/exceedance-of-air-quality-limit-3/assessment-5.

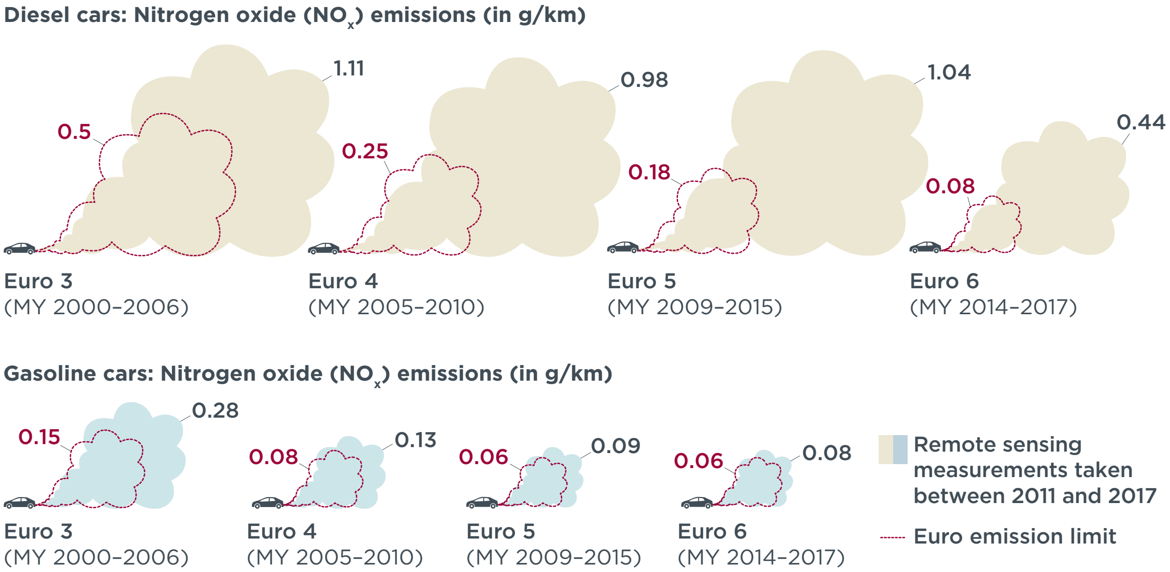
[4] World Health Organization, *Evolution of WHO air quality guidelines: Past, present and future* (Copenhagen, 2017), http://www.euro.who.int/__data/assets/pdf_file/0019/331660/Evolution-air-quality.pdf?ua=1.

[5] A. J. Haagen-Smit, "Chemistry and physiology of Los Angeles smog," *Industrial & Engineering Chemistry,* 1952, 44 (6): 1342–1346, https://doi.org/10.1021/ie50510a045.

It was not until 1970 that the matter was addressed with regulatory action at the European level. Directive 70/220/EEC established emission limits for CO and HC from gasoline-powered vehicles. The landmark directive was amended several times over the following decades to extend its scope: Emission limits for NO_x were introduced in 1977 (Directive 77/102/EEC), amendments to also cover the gaseous pollutants of diesel vehicles were passed in 1983 (Directive 88/436/EEC), and a particulate mass (PM) emissions limit was introduced for diesel vehicles in 1988 (Directive 88/436/EEC). In 1992, the introduction of what is known today as Euro 1 (Directive 91/441/EEC) marked a new regulatory era for pollution control. Since then, the European Union has moved quickly to further tighten emission limits in the Euro 2 (Directive 96/69/EC), Euro 3 and 4 (Directive 98/69/EC), and Euro 5 and 6 (Regulation 715/2007) standards.

Data from remote sensing, a technique for measuring emissions in real driving conditions, comprising hundreds of thousands of light-duty vehicles (LDVs)[6] suggest that Euro standards have been ineffective in reducing the real-world NO_x emissions from diesel vehicles. From 2000 to 2016, that is from Euro 3 to Euro 6, the nominal NO_x limits set by the diesel Euro standards have been reduced by 84%. However, NO_x emissions from transport have gone down only 32% in the same time period.[7]

As shown in Figure 2, real-world diesel NO_x emissions remained largely constant from Euro 3 through Euro 5. Although Euro 6 diesel vehicles show a reduction in NO_x compared to Euro 5, the real-world emissions are still several times above the Euro 6 limit. NO_x emissions from petrol vehicles, on the other hand, have decreased proportionally to reductions in the limit set by the applicable Euro standard.


Diesel cars: Nitrogen oxide (NO_x) emissions (in g/km)

Gasoline cars: Nitrogen oxide (NO_x) emissions (in g/km)

Figure 2. Nitrogen oxide (NO_x) emissions (in g/km) estimated via remote sensing of the on-road fleet, from Euro 3 to Euro 6, for EU passenger vehicles.

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[6] Yoann Bernard et al., "Determination of real-world emissions from passenger vehicles using remote sensing data" (TRUE Initiative, June 5, 2018), https://www.theicct.org/publications/real-world-emissions-using-remote-sensing-data.

[7] European Environment Agency, "Emissions of air pollutants from transport," October 4, 2018, https://www.eea.europa.eu/data-and-maps/indicators/transport-emissions-of-air-pollutants-8/transport-emissions-of-air-pollutants-6.

The European Commission is now turning its attention to the development of post-Euro 6 emission standards. The following sections present background information highlighting the need for action and detailed recommendations.

The recommendations cover several topics where the current light-duty vehicle emission standards should be strengthened. These topics include the emission of regulated, unregulated, and climate forcing pollutants; the testing regimes, data evaluation methods, and boundary conditions for demonstrating compliance with type-approval and in-service conformity testing; and measures to improve the durability, emissions performance, and compliance with the standards throughout the useful life of the vehicles.

Each of the following subsections presents a brief introduction to the issue, outlines the current status of the European regulation, compares the European standards with similar regulations in other markets, and presents a set of specific policy recommendations to improve the environmental performance of future emission standards.

WHAT TO REGULATE? POLLUTANTS AND LIMITS

EMISSION LIMITS FOR CURRENTLY REGULATED POLLUTANTS

What is the issue?

The emission limits of the current Euro 6 standards were adopted in 2007, more than a decade ago, and do not fully exploit the technology potential for emissions reduction. Advances in engine controls, thermal management, and catalyst technology in gasoline and diesel power trains allow reductions in pollutant emissions significantly below the levels mandated by Euro 6, as recently demonstrated on a diesel vehicle by the Association for Emissions Control by Catalyst.[8] A separate widely-publicized study[9] by Bosch, a leading automotive industry supplier, also indicates that significantly lower limits are technologically feasible. According to Bosch,[10] its diesel technology can achieve NO_x emissions of 13 mg/km over legally compliant on-road RDE tests.

Exhaust filters are another proven technology that reduces particulate emissions by orders of magnitude. However, filters have only been used in diesel power trains as the regulatory requirements have not yet forced the technology in gasoline power trains.[11]

In summary, the current technology landscape allows the introduction of significantly more stringent emission limits than those set by the Euro 6 standards.

The Euro standards traditionally have differentiated between positive ignition engines (e.g., gasoline engines) and compression ignition engines (diesel engines). The European Commission's reasoning behind this approach is that it is "more technically challenging to achieve effective emissions control from diesel engines."[12]

However, technology neutrality is a widely cited principle in several regulatory proposals put forward by the European Commission. To allow free and undistorted market competition for the development of compliance strategies, standards should not discriminate in favor of or against a particular type of technology. In the context of pollutant emission standards, the technology neutrality principle should translate into emission limits that are independent of fuel and application.

Current regulation

Table 2 shows the current Euro 6 emission limits for light-duty vehicles. Depending on the fuel type and application, different limits apply for NO_x, HC, and CO. For passenger vehicles (LDV columns in Table 2), the 80 mg/km NO_x limit applicable for diesel engines

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[8] J. Demuynck et al., "Integrated diesel system achieving ultra-low urban and motorway NO_x emissions on the road," (2019), http://www.aecc.eu/wp-content/uploads/2019/04/190516-AECC-IAV-IPA-Integrated-Diesel-System-achieving-Ultra-Low-NOx-on-the-road-Vienna-Symposium.pdf.

[9] Andreas Kufferath et al., "The path to a negligible NO_2 immission contribution from the diesel powertrain" (Robert Bosch GmbH, April 2018), https://www.autonews.com/assets/pdf/bosch-nox-report.pdf.

[10] Robert Bosch GmbH, "Breakthrough: New bosch diesel technology provides solution to NO_x problem," Bosch Media Service, April 25, 2018, https://www.bosch-presse.de/pressportal/de/en/breakthrough-new-bosch-diesel-technology-provides-solution-to-nox-problem-155524.html.

[11] Ameya Joshi and Timothy V. Johnson, "Gasoline particulate filters—A review," *Emission Control Science and Technology,* 2018, 4 (4), 219–39, https://doi.org/10.1007/s40825-018-0101-y.

[12] European Commission, "Impact assessment for Euro 6 emission limits for light duty vehicles" [Commission Staff Working Document], September 20, 2006, https://ec.europa.eu/growth/content/euro-5-and-6-will-reduce-emissions-diesel-cars-0_en.

is 33% higher than the limit for gasoline engines. Conversely, the 1,000 mg/km CO limit for positive ignition engines is twice as high as the compression ignition limit.

The current standards for gasoline engines, which have barely changed since Euro 4, make another important differentiation regarding the fuel injection technology. Whereas gasoline direct injection engines are subject to PM and particulate number (PN) limits, engines with indirect injection, also called port fuel injection (PFI) engines, do not need to comply with any particulate emissions requirement. However, gasoline engines with indirect injection can have PN emissions[13] above the regulatory limit for direct injected engines.

Table 2. Euro 6 emission limits for passenger cars and light-commercial vehicles

	LDVs, LCVs Class 1[a]		LCVs Class 2		LCVs Class 3	
	Gasoline[b]	Diesel[c]	Gasoline	Diesel	Gasoline	Diesel
NMHC (mg/km)	68	-	90	-	108	-
THC (mg/km)	100	-	130	-	160	-
NO_x (mg/km)	60	80	75	105	82	125
THC + NO_x (mg/km)	-	170	-	195	-	215
CO (mg/km)	1,000	500	1,810	630	2,270	740
PM (mg/km)	4.5[d]	4.5	4.5[d]	4.5	4.5[d]	4.5
PN (#/km)	6 × 10^{11}[d]	6 × 10^{11}	6 × 10^{11}[d]	6 × 10^{11}	6 × 10^{11}[d]	6 × 10^{11}

Notes: [a]Classes 1 through 3 are weight classes. [b]Gasoline is used as a proxy term for positive ignition (PI) engines. [c]Diesel is used as a proxy term for compression ignition (CI) engines. [d]Applicable to direct injection engines only.

International comparison

Figure 3 compares the LDV Euro 6 emission limits to the China 6[14] standards, and the Tier 3[15] standards in the United States. The comparison is done for the emission limits over the standard chassis dynamometer tests, a cold-started test on the chassis dynamometer at regular temperature, and does not take into consideration the differences in test cycles and procedures among various regulatory programs.

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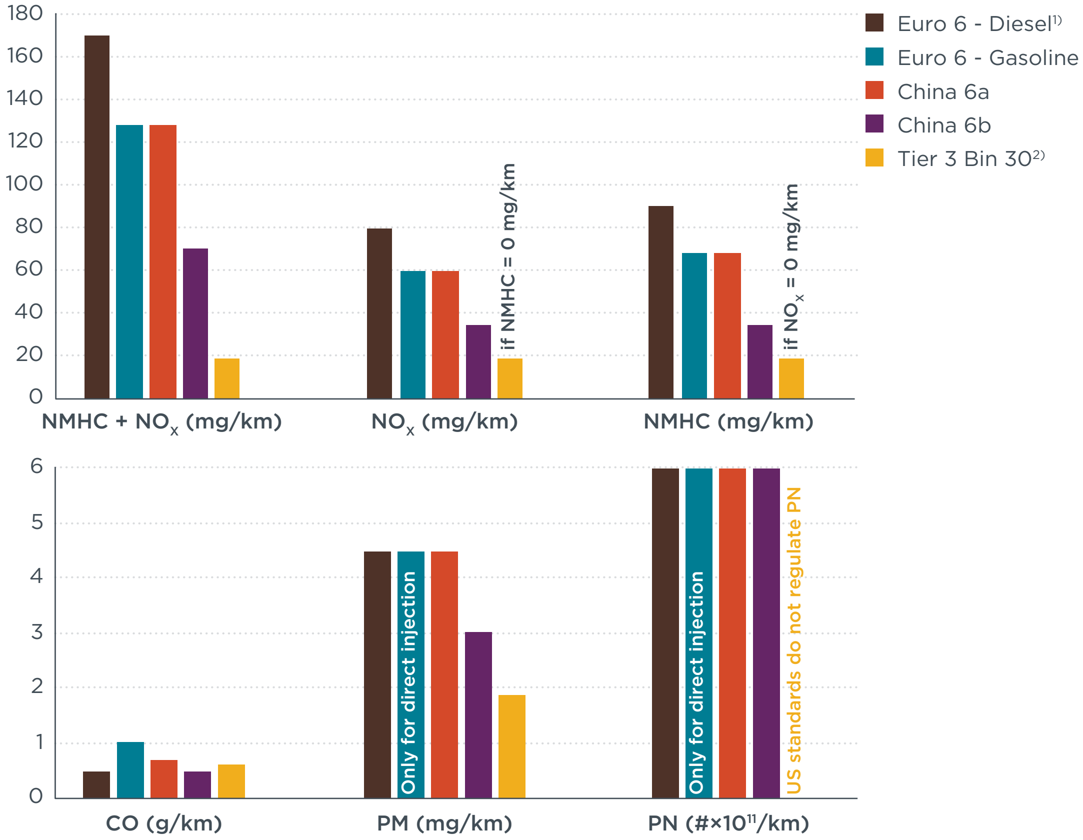
[13] Further details on the limitations of the current particulate emission standards can be found in a following section.

[14] MEE, "Limits and measurement methods for emissions from light-duty vehicles (CHINA 6)" (People's Republic of China, December 23, 2016), http://kjs.mee.gov.cn/hjbhbz/bzwb/dqhjbh/dqydywrwpfbz/201612/t20161223_369476.shtml.

[15] U.S. EPA, "Control of air pollution from motor vehicles: Tier 3 motor vehicle emission and fuel standards; Final rule," Federal Register, Vol. 79, No. 81, April 28, 2014, https://www.govinfo.gov/content/pkg/FR-2014-04-28/pdf/2014-06954.pdf.



NMHC: Non-methane hydrocarbons

NO$_x$: Nitrogen oxides

CO: Carbon monoxide

PM/PN: Particulate mass / number

1) Diesel engines have negligible methane emissions, therefore the NMHC and THC Euro 6 limits are assumed to be the same.The equivalent THC Euro 6 diesel limit is estimated by subtracting the NO$_x$ limit from the THC+NO$_x$ limit.

2) The United States regulates non-methane organic gases (NMOG), encompassing not only NMHC emissions but also other oxygenated HCs. US Tier 3 standards set limits for NMOG+NO$_x$. US standards are fleet averaged. Tier 3 fleet targets correspond to the emissions of Tier 3 Bin 30.

Figure 3. LDV emission limits according to the Euro 6, China 6, and U.S. Tier 3 standards

The U.S. Tier 3 and China 6 standards are both fuel neutral. The same emission limits apply to both gasoline and diesel power trains, without differentiating between direct and indirect injection engines. Moreover, the U.S. Tier 3 standards are also application neutral and do not differentiate light-duty vehicles from light commercial vehicles (called light-duty trucks in the United States) as Euro 6 and China 6 standards do. The Tier 3 limits apply to passenger vehicles with a gross vehicle weight up to circa 4,500 kg (10,000 lb) and for light-duty trucks up to circa 3,800 kg (8,500 lb).

The currently applicable Euro 6 NO$_x$ emission limits are more lenient than the adopted U.S. Tier 3 and China 6 standards. Although Euro 6 limits will allow diesel passenger cars to emit up to 80 mg/km of NO$_x$, China 6b limits, applicable from July 2023, set a technology-neutral limit of 35 mg/km per vehicle. The U.S. Tier 3 standards regulate NO$_x$ emissions in combination[16] with non-methane organic gases (NMOG). NMOG covers a

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[16] U.S. Tier 3 are fleet average standards that set limits for NMOG+NO$_x$. In 2025, after the phase-in period, the U.S. Tier 3 fleet average standards are equivalent to the Tier 3 Bin 30 level.

wider range of species than non-methane hydrocarbon limits (NMHC). Still, the limit set in the United States for 2025 is significantly more stringent than the China 6 limit. The U.S. Tier 3 standards allow a fleet averaged maximum of 19 mg/km for the combination of NMOG and NO_x. Similarly, NMHC of the Euro 6 standard are twice as high as the China 6b limit, and at least three times higher than the U.S. Tier 3 NO_x+NMOG combined limit.

Regarding particulate emissions, Europe has taken a leading role in introducing PN limits, effectively forcing the introduction of filters on diesel power trains. These provisions have been mirrored in the Chinese standards. Although no PN limit exists in the United States, California's LEV III standards set a PM limit of approximately 0.6 mg/km (1 mg/mi) over the federal test procedure (FTP) cycle, which is deemed comparable in stringency to Europe and China's PN limits. This limit will be fully phased in by 2028. The U.S. Tier 3 standard, which will be phased in by 2025, sets a PM limit of approximately 1.9 mg/km (3 mg/mi) over the same cycle. A more detailed discussion on the particulate emission limits is provided in the next section.

Recommendations

Future Euro standards provide an opportunity for the European Union to set its first technology-neutral standards, and to tighten the emission limits to levels close to the other two largest passenger vehicle markets, China and the United States. We offer the following recommendations:

» **Introduce fuel- and technology-neutral emission limits**. To ensure technology neutrality, future Euro standards should not make a differentiation between positive and compression ignition engines, or between the employed technology, such as direct or indirect engines. The U.S. Tier 3 and China 6 emission standards for light-duty vehicles already do so.

» **Tighten the emission limits to reflect technological advances and to catch up with other markets**. The current Euro 6 standards do not fully exploit the available technology potential for emissions reduction. As a result, the EU's emission limits are more lenient compared to the adopted standards in the United States and China. The development of post-Euro 6 standards provides an opportunity to align the limits with those of other major markets, forcing the development and deployment of emission control technologies that will better position the European manufacturers in those markets.

» **Introduce application-neutral emission limits.** Currently, light commercial vehicles (LCVs) with a maximum weight of 3.5 tonnes are allowed to emit up to 60% higher emissions than passenger LDVs with the same maximum weight. We recommend eliminating these wide differences in emission limits. The emission limits of LCVs, regardless of the weight class, should be set at the same level as passenger vehicles, as is the case in the United States. There are no technology barriers nor a solid technical argument to justify this differentiation between light-duty and light commercial vehicles.

ULTRAFINE PARTICULATE EMISSIONS

What is the issue?

Particulate emissions from mobile sources have direct consequences on the health and well-being of citizens. Epidemiological studies show that atmospheric particulate matter is directly linked to premature death and disease in urban populations and that there is no safe exposure threshold to small particle pollution.[17] The health effects of particulate emissions are caused by the chemical and physical interactions of primary and secondary particles that can induce irritation or damage when inhaled. Primary particles are those emitted directly by vehicles. Secondary particles are those formed from primary particles and other gaseous pollutants through complex atmospheric processes. As shown in Figure 4, the ability of inhaled particles to be captured within the human body, call the deposition efficiency, is a function of particle size.[18] Vehicle exhaust, in particular that of gasoline direct injection (GDI) engines, contains copious amounts of particles in the size ranges with high deposition efficiency.[19]

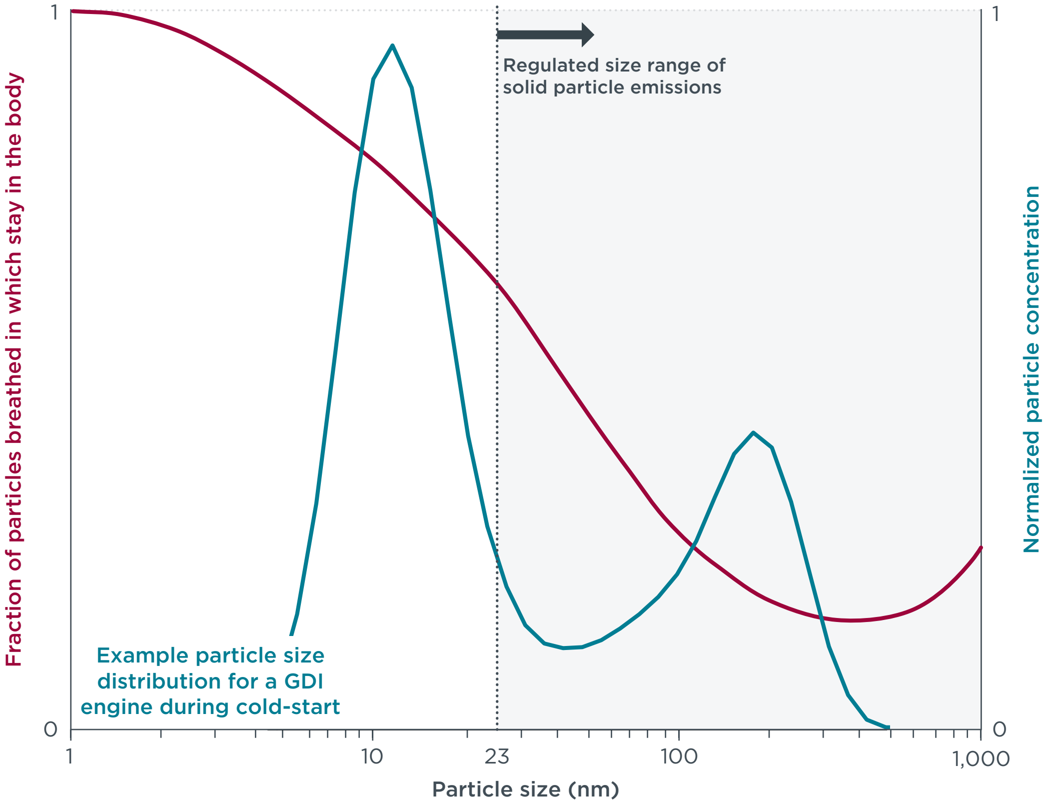

Figure 4. Mathematical model of particle deposition efficiency via nasal breathing in the lung by particle size (U.S. EPA, 2014) and an example of the particle size distribution of a GDI engine during cold-start (Rodríguez, 2016).

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[17] World Health Organization, *Ambient air pollution: A global assessment of exposure and burden of disease*.

[18] U.S. EPA, "Particle pollution exposure," Collections and Lists, September 15, 2014, https://www.epa.gov/pmcourse/particle-pollution-exposure.

[19] J. Felipe Rodríguez, "Investigations on the pollutant emissions of gasoline direct injection engines during cold-start" (Thesis, Massachusetts Institute of Technology, 2016), http://dspace.mit.edu/handle/1721.1/104130.

Particles smaller than 100 nm are much more likely to be captured within the human body, where they can cause damage, with the particle deposition efficiency rapidly increasing as the particles become smaller and smaller. These ultrafine particles are deemed to be the most damaging because they are most likely to be deposited within the human body, and they also have a large surface-to-volume ratio, which appears to be correlated with the biological activity of particles within the body.[20]

The current Euro standards leave a significant portion of PN emissions unregulated. As further explained below, the standards exclude all volatile and semi-volatile particles, solid particles smaller than 23 nm, particles emitted by gas-powered and port-fuel injection (PFI) gasoline engines, and particles emitted during the regeneration of particulate filters.[21]

Current PN limits only take into account solid particles larger than 23 nm. That is, volatile, semi-volatile, and solid particles smaller than 23 nm are currently not regulated. These unregulated particles can have detrimental health effects, not only through direct exposure, but also because of their role in the formation of secondary aerosols and $PM_{2.5}$.

The sub-23 nm size fraction is of particular relevance given the higher particle deposition efficiency in the human body (see Figure 4), and the higher toxicity of smaller particles. Recent tests[22] show that, compared to solid particles larger than 23 nm, the number of solid particles between 10 and 23 nm can be up to 260% higher for GDI engines, up to 330% higher for gas engines for which no particle limits apply, and up to 60% for diesel engines equipped with particle filters. The same data show that these ratios increase dramatically if smaller solid particles ranging between 2.5 and 23 nm are considered.

Particulate emissions of diesel engines have been successfully reduced through the wide adoption of diesel particulate filters (DPF), forced by the Euro PN limits. The regulation, however, has not driven the introduction of gasoline particulate filters (GPF). Modern, non-GPF, gasoline engines emit copious amounts of volatile and solid particles.[23] Of particular concern are PFI engines, for which no particle emission limits apply. A recent study[24] found that PN emissions from PFI engines can exceed the PN limits applicable for diesel and gasoline GDI vehicles.

Experimental results[25] have shown that particle emission during test phases where filter regeneration take place can exceed many times the regulatory limit. However, and contrary to other pollutants, particle number emissions during regeneration are not currently considered in the emission standards.

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[20] Richard W. Baldauf et al., "Ultrafine particle metrics and research considerations: Review of the 2015 UFP workshop," *International Journal of Environmental Research and Public Health,* 2016, 13 (11), https://doi.org/10.3390/ijerph13111054.

[21] Barouch Giechaskiel et al., "European regulatory framework and particulate matter emissions of gasoline light-duty vehicles: A review," *Catalysts,* 2019, 9 (7): 586, https://doi.org/10.3390/catal9070586.

[22] Leonidas Ntziachristos et al., "Gaseous and particulate pollutant measurements on the road and in the lab from latest car technologies in Europe" (Motor Vehicle/Vessel Emissions Control Workshop, Chengdu, China, 2019), https://www.move2019.org/assets/doc/presentation/6%20D2A%20Ntziachristos_Emissions.pdf.

[23] Barouch Giechaskiel et al., "Investigation of vehicle exhaust Sub-23 Nm particle emissions," *Aerosol Science and Technology,* 2017, 51 (5): 626–641, https://doi.org/10.1080/02786826.2017.1286291.

[24] Ricardo Suarez-Bertoa et al., "On-road emissions of passenger cars beyond the boundary conditions of the real-driving emissions test," *Environmental Research*, 2019, 176, 108572, https://doi.org/10.1016/j.envres.2019.108572.

[25] Barouch Giechaskiel et al., "Particle number measurements in the European legislation and future JRC activities," *Combustion Engines*, 2018, 174 (3): 3–16, https://doi.org/10.19206/CE-2018-301.

Current regulation

A PN limit[26] for gasoline direct injection engines was introduced in the Euro 6 standards. Contrary to the diesel case, the limit was not stringent enough to force the introduction of GPFs, and manufacturers have been able to meet the PN limit with engine measures alone. In RDE tests, gasoline vehicles can have substantially higher particulate emissions, when compared to laboratory tests.[27] Thus, the recent introduction of the RDE regulatory framework[28] is expected to drive a wide deployment of GPFs. Indirect injection engines, such as PFI and engines using gaseous fuels, are not subject to any particle emission limit.

The current regulatory method for determining PN is based on the work of the United Nations Economic Commission for Europe (UNECE) Particle Measurement Programme (PMP). The methodology establishes that the measurements are to be conducted in the diluted exhaust, that the volatile and semi-volatile particles are to be removed from the sample, and that only solid particles larger than 23 nm are to be taken into account. The size threshold was set at 23 nm because of the repeatability and reproducibility requirements of legislative procedures. Volatile particles were excluded for the same reason. However, the substantial presence of sub-23 nm particles, both volatile and solid, is undisputed.

International comparison

The European Union is at the vanguard when it comes to regulating the number of particles emitted by combustion engines. Several regions have included the EU's PN provisions in their own legislation. With its leading participation in UNECE's PMP group, the European Commission is well positioned to extend the scope of the PN measurement methodology to capture particles smaller than 23 nm.

The China 6 standards are technology-neutral. Therefore, PN limits will apply to gasoline vehicles regardless if they equip a direct or indirect injection engine starting in 2020.

Recommendations

The scope of the current Euro standards leaves a significant fraction of PN emissions unregulated. Positive ignition engines, regardless of the type of fuel or injection technology, emit a large number of particles, particularly in the sub-23 nm size range. Because particle filters reduce PN in a wide size spectrum and have higher filtration efficiencies at lower sizes,[29] there is no technology barrier to meeting emission limits that include sub-23 nm particles. We offer the following recommendations:

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[26] European Commission, "Commission Regulation (EU) No 459/2012 of 29 May 2012 Amending Regulation (EC) No 715/2007 of the European Parliament and of the Council and Commission Regulation (EC) No 692/2008 as Regards Emissions from Light Passenger and Commercial Vehicles (Euro 6) Text with EEA Relevance," *Official Journal of the European Union* L 142 (May 29, 2012), http://data.europa.eu/eli/reg/2012/459/oj.

[27] FEV, "RDE-conform gasoline engines. Gasoline particulate filters," *FEV Corporate Magazine* (blog), November 21, 2018, http://magazine.fev.com/en/gasoline-particulate-filters/.

[28] European Commission, "Commission Regulation (EU) 2017/1151 of 1 June 2017 Supplementing Regulation (EC) No 715/2007 of the European Parliament and of the Council on Type-Approval of Motor Vehicles with Respect to Emissions from Light Passenger and Commercial Vehicles (Euro 5 and Euro 6) and on Access to Vehicle Repair and Maintenance Information, Amending Directive 2007/46/EC of the European Parliament and of the Council, Commission Regulation (EC) No 692/2008 and Commission Regulation (EU) No 1230/2012 and Repealing Commission Regulation (EC) No 692/2008 (Text with EEA Relevance), *Official Journal of the European Union* L 175 (June 1, 2017), http://data.europa.eu/eli/reg/2017/1151/oj.

[29] Association for Emissions Control by Catalyst, "Gasoline particulate filter (GPF)" (2017). https://www.aecc.eu/wp-content/uploads/2017/11/2017-AECC-technical-summary-on-GPF-final.pdf.

» **Lower the size cutoff for particle counting from 23 nm to at least 10 nm.** The results of UNECE's PMP group suggest that lowering the size threshold from 23 nm to 10 nm for solid particles is possible without large investment costs or significant modifications to existing measurement systems. As the particle counting techniques continue to evolve, measuring in the sub-10 nm range will likely be feasible. Future standards should allow the inclusion of particles smaller than 10 nm through implementing acts.

» **Develop a measurement methodology for volatile and semi-volatile particles, allowing for their inclusion in the regulatory framework.** Even if the current particle counting methodologies do not allow a robust and repeatable measurement of non-solid particles, future Euro standards can enable the inclusion of volatile and semi-volatile particles through implementing acts, once technically feasible.

» **Include emissions that occur during filter regeneration**. The contribution of the particle emissions during regeneration can be significant. It is, therefore, important to consider PN emissions during regeneration in future emission standards, in the same way that other pollutants are already considered. The current PN measurement methodology is applicable during regeneration events, and no new test protocol would be required.

» **Make PN standards fuel- and technology-neutral.** PFI and gas-fueled engines emit significant amounts of ultrafine particles. To ensure technology neutrality, future Euro standards should follow China 6's lead and set the same limits for all engines regardless of fuel type or fuel injection technology.

» **Investigate the feasibility of PN tailpipe measurements.** Currently, laboratory PN emissions are measured in the dilution tunnel. In the transfer from the tailpipe to the dilution tunnel, particle losses occur. Because on-road RDE measurements are done at the tailpipe, the measurement of tailpipe PN in the laboratory would improve the comparability of on-road and laboratory results and improve the robustness of the PN-portable emissions measurement system (PEMS) uncertainty framework used for the determination of RDE conformity factors. Recent results suggest that, compared to dilution tunnel measurements, tailpipe sampling does not increase the uncertainty level and that the measurements are more representative.[30]

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[30] Barouch Giechaskiel, Tero Lähde, and Yannis Drossinos, "Regulating particle number measurements from the tailpipe of light-duty vehicles: The next step?" *Environmental Research,* 2019, 172: 1–9, https://doi.org/10.1016/j.envres.2019.02.006.

AMMONIA EMISSIONS

What is the issue?

Although ammonia is not a byproduct of the combustion process, it is formed in substantial quantities in the emission control systems of gasoline and diesel vehicles. These ammonia emissions can be a threat to urban air quality, given ammonia's significant role in the formation of secondary particles.

Agricultural activity is the main overall source of ammonia emissions. However, motor vehicles can surpass the agricultural sector as the main source of ammonia in European cities.[31] Because urban centers are typically ammonia-limited environments, emitted ammonia readily reacts in the atmosphere to form secondary particles, such as ammonium nitrate and ammonium sulfate, increasing $PM_{2.5}$ levels.[32] A milligram of ammonia is estimated to convert into one milligram of $PM_{2.5}$ in the atmosphere.[33]

As shown in Figure 5, ammonia is becoming the main fixed nitrogen species emitted by modern gasoline engines.[34] This is likely driven by reductions in NO_x emissions and the absence of ammonia emission limits.

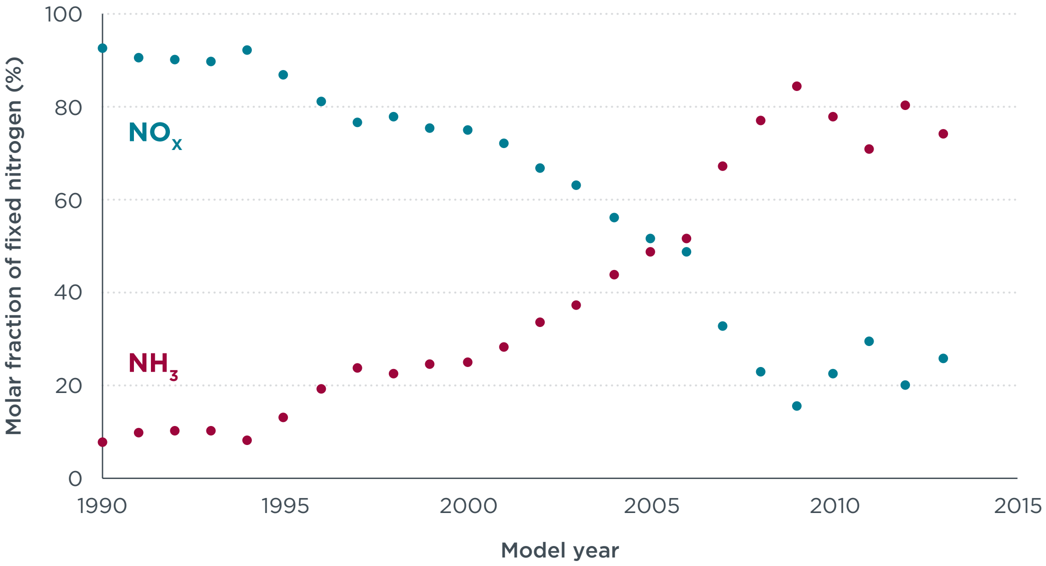

Figure 5. Molar contributions of NO_x and NH_3 to fixed nitrogen emissions of gasoline vehicles, as a function of vehicle model year. Adapted from Bishop and Stedman (2015).

Ammonia is formed in the three-way-catalyst of gasoline engines during fuel-rich events with high exhaust temperatures, such as those founds during aggressive acceleration or

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[31] Miriam Elser et al., "High contributions of vehicular emissions to ammonia in three European cities derived from mobile measurements," *Atmospheric Environment,* 2018, 175: 210–220, https://doi.org/10.1016/j.atmosenv.2017.11.030.

[32] Ricardo Suarez-Bertoa et al., "On-road measurement of NH_3 emissions from gasoline and diesel passenger cars during real world driving conditions," *Atmospheric Environment,* 2017, 166: 488–497, https://doi.org/10.1016/j.atmosenv.2017.07.056.

[33] Ricardo Suarez-Bertoa, "Current non-regulated emissions in EU" (Integer Emissions Summit & AdBlue® Europe 2019, Munich, 2019).

[34] Gary A. Bishop and Donald H. Stedman, "Reactive nitrogen species emission trends in three light-/medium-duty united States fleets," *Environmental Science & Technology,* 2015, 49 (18): 11234–11240, https://doi.org/10.1021/acs.est.5b02392.

high sustained engine load. Diesel ammonia emissions are produced by lean NO_x traps (LNT) during regeneration and cold start, and by selective catalytic reducers (SCR) requiring gaseous ammonia, typically created by decomposing a urea solution such as AdBlue. Moreover, the introduction of the RDE regulation will require higher SCR conversion efficiencies, which can lead to more aggressive dosing of urea and increase the likelihood of ammonia slip.

Current regulation

A test protocol already exists to measure ammonia emissions in the laboratory. However, ammonia is not regulated in the light-duty Euro 6 standards. Heavy-duty engines, in contrast, are subject to an average concentration limit of 10 ppm.

International comparison

The efforts to limit ammonia emissions from motor vehicles have been mostly limited to heavy-duty engines. Brazil and Korea are the only jurisdictions to have set ammonia limits for passenger vehicles. From the entry into force of the PROCONVE L8 Phase[35] in 2025, ammonia emissions of diesel vehicles equipped with SCR systems will be limited to 10 ppm, measured as the average value in the certification cycle. In Korea, ammonia emissions from all passenger cars with a gross weight over 3.5 tonnes are limited to 10 ppm, averaged over the certification cycle.[36]

Recommendations

Ammonia emissions are a significant source of fixed nitrogen emissions from motor vehicles, with consequences in urban air quality due to the role of ammonia in the formation of secondary particles. We offer the following recommendation:

» **Introduce technology- and application-neutral limits for ammonia emissions.** A distance-specific limit in mg/km is suggested in combination with an average concentration limit in ppm to avoid ammonia spikes and their associated unpleasant odor. Pilot tests using portable systems show that ammonia measurements could also be included in future RDE procedures.[37]

METHANE AND NITROUS OXIDE EMISSIONS

What is the issue?

Methane (CH_4) and nitrous oxide (N_2O) are both powerful greenhouse gases (GHGs) that can be found in significant quantities in the exhaust of motor vehicles. The global warming potentials (GWPs) of CH_4, which reflect how much more heat is trapped by CH_4 than by carbon dioxide (CO_2), are 84 when considering a 20-year time horizon and 28 in a 100-year period. The 20- and 100-year GWPs of N_2O are significantly higher at 264 and 265, respectively.[38]

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[35] Ministério do Meio Ambiente and Conselho Nacional do Meio Ambiente, “RESOLUÇÃO Nº 492, DE 20 DE DEZEMBRO DE 2018,” *Diário Oficial Da União* 246 (December 24, 2018): 141, http://www.in.gov.br/materia/-/asset_publisher/Kujrw0TZC2Mb/content/id/56643907

[36] Ministry of Environment, Republic of Korea, “Enforcement Rules of the Air Quality Preservation Act,” Pub. L. No. Decree No. 583 (2015), http://www.law.go.kr/lsInfoP.do?lsiSeq=165622&efYd=20150101#AJAX.

[37] Suarez-Bertoa et al., “On-road measurement of NH_3 emissions from gasoline and diesel passenger cars during real world driving conditions.”

[38] IPCC, “Climate change 2013: The physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change” (Cambridge University Press, 2013), https://www.ipcc.ch/report/ar5/wg1/

Methane emissions are the result of incomplete combustion. Because CH_4 is a relatively stable molecule, catalytic converters are less effective at oxidizing CH_4 than other longer-chained hydrocarbons. N_2O, on the other hand, forms inside emission control systems. During the catalytic reduction of NO_x to nitrogen, N_2O forms as an intermediate, unwanted product.

N_2O emissions from passenger cars in Europe are estimated using emission factors that translate the distances travelled by vehicles into N_2O emissions. However, the N_2O emission factors used in national inventories for road transport are considered highly uncertain.[39] In particular, estimating the level and trend of N_2O emission from diesel vehicles equipped with SCR systems is not presently possible.[40] Current emission inventories estimate N_2O emission to be 4.6 million tonnes of CO_2-equivalent in 2017,[41] approximately 1% of direct CO_2 emissions. However, these estimates do not capture the influence of modern diesel and gasoline emission control systems on N_2O emissions. For example, diesel engines equipped with ammonia slip catalysts can have N_2O emissions equivalent to 30% of direct CO_2 emissions.[42] Similarly, the use of rhodium and palladium instead of platinum in three-way catalysts of gasoline vehicles also leads to higher N_2O emissions.[43]

Current regulation

Methane emissions are implicitly regulated in current emissions legislation in the European Union, as the total HC emissions are regulated. Particularly for vehicles with positive ignition, the Euro 6 standards set a 100 mg/km limit for total HC emissions and a 68 mg/km limit for non-methane HC emissions. However, the purpose of these limits is not to reduce the climate-forcing impacts of CH_4 but rather to limit the emission of other more reactive and toxic hydrocarbons.

N_2O emissions are not regulated in the current emissions legislation in the European Union.

International comparison

The U.S. Environmental Protection Agency established limits for light-duty emissions of N_2O and CH_4, applicable to vehicles from model year 2012 onward, as part of the greenhouse gas emission standards.[44] The applicable limit in the United States is 6.3 mg/km (10 mg/mile) for N_2O and 18.8 mg/km (30 mg/mile) for CH_4 over the FTP cycle. The most recent Chinese emission standards, China 6,[45] limit N_2O emissions to 20 mg/km.

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[39] United Nations Framework Convention on Climate Change, "Estimation of emissions from road transport," June 3, 2004, https://unfccc.int/resource/docs/2004/sbsta/inf03.pdf.

[40] European Environment Agency, "Passenger cars, light commercial trucks, heavy-duty vehicles Including buses and motor cycles," in *EMEP/EEA Air Pollutant Emission Inventory Guidebook 2016: Technical Guidance to Prepare National Emission Inventories*, 2018, https://www.eea.europa.eu/publications/emep-eea-guidebook-2016.

[41] European Environment Agency, "National emissions reported to the UNFCCC and to the EU greenhouse gas monitoring mechanism," May 29, 2019, https://www.eea.europa.eu/data-and-maps/data/national-emissions-reported-to-the-unfccc-and-to-the-eu-greenhouse-gas-monitoring-mechanism-15.

[42] Rolf Hagman and Astrid Helene Amundsen, "Emissions from vehicles with Euro 6/VI technology - Test Phase 2," December 2013, https://www.toi.no/publications/emissions-from-vehicles-with-euro-6-vi-technology-test-phase-2-article32442-29.html.

[43] Felipe Rodríguez and Jan Dornoff, *Beyond NO_x: Emissions of Unregulated Pollutants from a Modern Gasoline Car*, (ICCT: Washington, DC, May 2019), https://www.theicct.org/publications/beyond-nox-emissions-unregulated-pollutants.

[44] U.S. EPA and U.S. DOT, "2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards; Final Rule," October 15, 2012, https://www.govinfo.gov/content/pkg/FR-2012-10-15/pdf/2012-21972.pdf.

[45] MEE, "China 6 Emission Standards."

Recommendations

CH_4 and N_2O emissions can both be found in non-negligible amounts in motor vehicle exhaust. Because both species have a strong global warming potential, their contribution to the climate impact of motor vehicles should receive closer examination. We offer the following recommendation:

» **Introduce technology- and application-neutral limits for methane and nitrous oxide emissions and account for their CO_2-equivalent emissions in the CO_2 standards.** Nitrous oxide and methane limits already exist in the United States and China, and it is recommended that the European Union include these pollutants in its regulatory framework as well. A test protocol already exists to measure methane and nitrous oxide emissions in the laboratory. The future use of portable systems can provide an avenue to include these pollutants in the RDE framework.

EMISSION OF ALDEHYDES AND OTHER VOLATILE ORGANIC COMPOUNDS

What is the issue?

Atmospheric aldehydes, a group of highly toxic compounds, are mainly a consequence of direct emissions from industrial and mobile sources. Exposure to aldehydes presents a significant health risk, as they are genotoxic agents: Aldehydes can cause nasopharyngeal cancer in humans and have been shown to instigate respiratory carcinomas in rodent models.[46]

Aldehyde emissions from spark-ignited engines, predominantly formaldehyde and acetaldehyde, occur primarily during the cold-start phase and are the result of the incomplete burning of the alcohol content of the fuel. It has been shown that higher ethanol content in fuel blends leads to higher aldehyde emissions.[47] The dominant EU gasoline blend has an ethanol content of 5% (E5). However, blends with 10% ethanol (E10) are gaining traction,[48] modern vehicles already can run on blends containing up to 15% (E15),[49] and flex-fuel vehicles able to operate on 85% ethanol blends (E85) are available in the market, although with a declining market share.

In light of the increasing ethanol content of the fuel, it is not clear if current emission inventories for VOCs, which rely on speciation data from more than 20 years ago,[50] accurately capture transport's contribution to overall aldehyde emissions.

Current regulation

Vehicular aldehyde emissions are not regulated. Aldehydes contain oxygen atoms in their molecular structure; thus, they are not part of the regulated family of hydrocarbons and belong to a larger group of chemicals known as volatile organic compounds (VOC).

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[46] Richard M. LoPachin and Terrence Gavin, "Molecular mechanisms of aldehyde toxicity: A chemical perspective," *Chemical Research in Toxicology*, 2014, 27 (7): 1081–1091, https://doi.org/10.1021/tx5001046.

[47] Sergio Manzetti and Otto Andersen, "A review of emission products from bioethanol and its blends with gasoline. Background for new guidelines for emission control," *Fuel,* 2015, 140: 293–301, https://doi.org/10.1016/j.fuel.2014.09.101.

[48] Susan Phillips et al., "EU-28 biofuels annual EU biofuels annual 2018" (Global Agricultural Information Network, July 3, 2018), https://www.fas.usda.gov/data/eu-28-biofuels-annual-0.

[49] Ricardo Suarez-Bertoa et al., "Intercomparison of ethanol, formaldehyde and acetaldehyde measurements from a flex-fuel vehicle exhaust during the WLTC," *Fuel,* 2017, 203: 330–340, https://doi.org/10.1016/j.fuel.2017.04.131.

[50] European Environment Agency, "Passenger cars, light commercial trucks, heavy-duty vehicles including buses and motor cycles."

The EU regulation considers HC emissions to be whatever is measured by the exhaust analyzer, called a flame ionization detector (FID). Although this technique accurately measures total HC emissions, it underestimates the concentration of oxygenated VOCs, such as aldehydes and ethanol. Hence, the current approach to measuring HC emissions solely with FIDs leads to an incorrect estimation of actual VOC emission of vehicles using ethanol blends. This underestimation has been shown to be as high as 74% when high-ethanol blends are used (e.g., E85).[51] Still, the test protocols required to accurately measure aldehydes and other oxygenated VOCs are available as they have already been developed in the context of UNECE's Global Technical Regulations.[52]

International comparison

Three large markets have established aldehyde emission limits. The U.S. Tier 3 standards set a formaldehyde limit of 4 mg/mi,[53] Brazil's PROCONVE L7 regulation a limit of 15 mg/km for the combined emissions of formaldehyde and acetaldehyde,[54] and Korea a formaldehyde limit of 7 mg/km in the K-LEVIII standards.[55]

The United States and Korea not only regulate total HC emissions and NMHC but set limits for the wider encompassing category of NMOG emissions, which includes aldehydes.

Recommendations

The current regulatory framework underestimates the VOC emissions of vehicles fueled with high-ethanol blends and does not consider the emissions of highly toxic aldehyde compounds. We offer the following recommendations:

- **Introduce technology- and application-neutral limits for aldehyde emissions.** Aldehyde emissions increase with the ethanol content of the fuel blend. A technology- and application-neutral aldehyde limit reduces the risk that higher ethanol blends, or an uptake in flex-fuel vehicles, increases in atmospheric concentration of these genotoxic compounds.
- **Extend the regulatory framework to include all VOC emissions.** Euro standards have historically set limits for only hydrocarbon emissions and have disregarded the emissions of other volatile organic compounds. It is recommended that future emission standards set limits for NMOG emissions, and not just total HC and NMHC.

TIRE AND BRAKE PARTICLES

What is the issue?

Engine combustion is not the only source of particulate emissions from road vehicles. Tire, brake, clutch, and road surface wear is also a significant source of ultrafine particles. Some of these particles are light enough to become airborne, while others are deposited on the road surface. Deposited particles can be resuspended by vehicles driving over them and by wind streams. Brake wear, in particular, has been recognized

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[51] Suarez-Bertoa et al., "Intercomparison of ethanol, formaldehyde and acetaldehyde measurements from a flex-fuel vehicle exhaust during the WLTC."

[52] United Nations Economic Commission for Europe, "Addendum 15: Global Technical Regulation No. 15," 2014, https://www.unece.org/fileadmin/DAM/trans/main/wp29/wp29r-1998agr-rules/ECE-TRANS-180a15e.pdf.

[53] U.S. EPA, "Control of Air Pollution From Motor Vehicles: Tier 3 Motor Vehicle Emission and Fuel Standards."

[54] Ministério do Meio Ambiente and Conselho Nacional do Meio Ambiente, "RESOLUÇÃO Nº 492."

[55] Ministry of Environment, Republic of Korea, "Enforcement Rules of the Air Quality Preservation Act."

as the leading source of non-exhaust particles, contributing up to 21% of all PM_{10} emissions related to traffic.[56]

Current regulation

A measurement procedure for brake wear particle emission is under discussion in UNECE's PMP. The first task will be to define a brake dynamometer test that simulates typical braking behavior in light-duty vehicles, followed by a methodology for measuring the particle emissions during the test.

International comparison

California's Vehicle Emissions Research Program also is carrying out research to gain a better understanding of the most important factors affecting the emissions from non-exhaust sources.[57]

Recommendations

As the emission of particles from combustion engines declines, driven by more stringent pollutant standards, the relative contribution of brake wear particles to the total particulate emissions due to vehicles increases. We offer the following recommendation:

» **Establish emission limits for brake wear particles.** Although a robust methodology for testing and measuring particles related to brake wear does not yet exist, future Euro standards should strive to include non-exhaust emissions within the regulatory framework, with a special emphasis on brake wear particles.

PRIMARY NO_2 STANDARDS

What is the issue?

NO_x emissions are a mix of nitric oxide (NO) and nitrogen dioxide (NO_2). Although NO_x is primarily emitted as NO, the oxidizing power of the atmosphere converts NO to NO_2 usually within one hour.[58] The short atmospheric life of NO has led policymakers to focus on NO_x emissions as a whole, without differentiating between NO and NO_2. However, the increase in the NO_2 to NO ratio of vehicle exhaust[59] due to changes in emission control technology (see Figure 6), the exceedance of NO_2 air quality limits in many urban areas,[60] and the better epidemiological understanding of the effects of NO_2 exposure on children[61] and adults,[62] warrant a deeper examination of direct NO_2 emissions. Furthermore, the increase in the NO_2-to-NO_x ratio of diesel vehicles has led to higher ground-level ozone concentrations in several air quality measurement stations monitoring pollution from traffic in the European Union.[63]

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[56] Theodoros Grigoratos and Giorgio Martini, "Brake wear particle emissions: A review," *Environmental Science and Pollution Research*, 2015, 22 (4): 2491–2504, https://doi.org/10.1007/s11356-014-3696-8.

[57] California Air Resources Board, "Brake & tire wear emissions," https://ww2.arb.ca.gov/resources/documents/brake-tire-wear-emissions.

[58] Kinga Skalska, Jacek S. Miller, and Stanisław Ledakowicz, "Kinetics of nitric oxide oxidation," *Chemical Papers,* 2010, 64 (2): 269–272, https://doi.org/10.2478/s11696-009-0105-8.

[59] Bernard et al., "Determination of real-world emissions from passenger vehicles using remote sensing data."

[60] European Environment Agency, "Exceedance of air quality standards in urban areas."

[61] Pattanun Achakulwisut et al., "Global, national, and urban burdens of paediatric asthma incidence attributable to ambient NO_2 pollution: Estimates from global datasets," *The Lancet Planetary Health,* 2019, 3 (4): e166-e168, https://doi.org/10.1016/S2542-5196(19)30046-4.

[62] Ki-Do Eum et al., "Long-term NO_2 exposures and cause-specific mortality in American older adults," *Environment International,* 2019, 124: 10–15, https://doi.org/10.1016/j.envint.2018.12.060.

[63] European Environment Agency, *Air Quality in Europe — 2018 Report*.

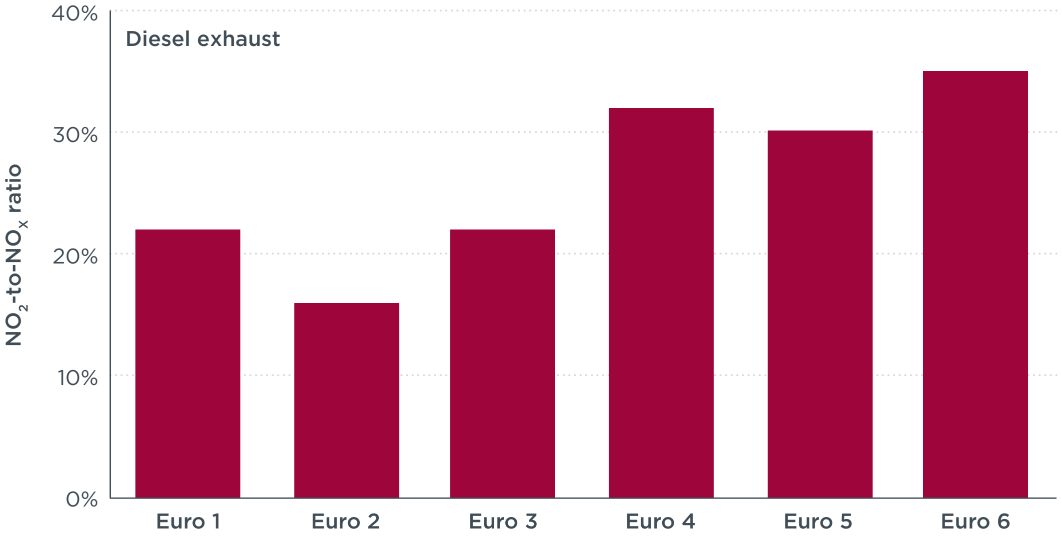

Figure 6. NO_2-to-NO_x ratio for diesel passenger vehicles for the different Euro standards. The ratios were estimated from remote sensing data gathered by TRUE Initiative.

As shown in Figure 6, the contribution of NO_2 to total NO_x emissions from diesel powered vehicles has been on the rise for the past decades, mainly due to technology changes in emission control systems.[64] However, high NO_2 fractions can be desirable in the exhaust of diesel engines to passively regenerate DPFs and to increase the efficiency of NO_x control systems. To control the NO_2-to-NO_x ratio, aftertreatment systems rely on oxidation catalysts that convert a significant amount of the NO coming from the engine into NO_2.

Current regulation

The Euro 6 standards set limits on total NO_x emissions, but do not set separate limits for direct NO_2 emissions. Recognizing the high and increasing share of NO_2 in the total NO_x emissions of modern diesel vehicles, the European Commission sought to introduce NO_2 emission limits in 2014.[65] However, the regulatory initiative was stalled despite the positive parliamentary report[66] on the proposal. It is unclear whether the proposal will be taken up again before a more comprehensive post-Euro 6 proposal is released. NO_2 and NO currently are measured individually in laboratory on-road tests. Thus, an NO_2 limit would not imply any modification of the test procedures.

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[64] David C. Carslaw et al., "Have vehicle emissions of primary NO_2 peaked?" *Faraday Discussions,* 2016, 189: 439–454, https://doi.org/10.1039/c5fd00162e.

[65] European Commission, "Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL Amending Regulations (EC) No 715/2007 and (EC) No 595/2009 as Regards the Reduction of Pollutant Emissions from Road Vehicles," January 31, 2014, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52014PC0028.

[66] Committee on the Environment, Public Health and Food Safety, "REPORT on the Proposal for a Regulation of the European Parliament and of the Council Amending Regulations (EC) No 715/2007 and (EC) No 595/2009 as Regards the Reduction of Pollutant Emissions from Road Vehicles" (European Parliament, September 29, 2015), http://www.europarl.europa.eu/doceo/document/A-8-2015-0270_EN.html?redirect.

International comparison

There are no primary NO_2 limits in any pollutant emission standards around the world. In 2009, the United States implemented[67] NO_2 limits for retrofit technologies. The requirement limited the increase in NO_2 emissions associated with some retrofit technologies to 20% of the engine NO_2 levels without the retrofit.

Recommendations

A reduction of primary NO_2 emissions can reduce the direct exposure to this pollutant in the proximity of transited roads. This also can reduce ground-level ozone formation. However, mandating reductions in primary NO_2 emissions can put further constraints on the design of emission control systems. We offer the following recommendation:

» **Consider technology- and application-neutral limits for NO_2 emissions.** In addition to the existing limit for total NO_x emissions, an NO_2 limit should be considered, taking into account the technical feasibility, the data available on the NO_2-to-NO_x ratio of Euro 6 vehicles, and the impacts on other pollutants.

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[67] U.S. EPA, "Nitrogen dioxide limits from retrofit technologies" (United States Environmental Protection Agency, Office of Air and Radiation, December 20, 2007), http://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100K4C5.PDF.

EVAPORATIVE EMISSIONS REQUIREMENTS FOR GASOLINE PASSENGER VEHICLES

What is the issue?

Evaporative emissions occur when vapor generated in the fuel system of gasoline vehicles is vented to the atmosphere, either directly or as permeation through tanks and hoses. These volatile hydrocarbons contribute to ozone and $PM_{2.5}$, as they easily convert into secondary organic aerosols. Diesel fuel has a low volatility, and evaporative emissions of diesel vehicles are not of concern.

Evaporative emissions usually are grouped into three separate categories according to the main heat source driving the vapor generation in the fuel system: diurnal emissions, running losses, and hot-soak emissions. Refueling emissions, another source of evaporative emissions, result from the displacement of fuel vapors during tank filling and minor fuel drips. Figure 7 shows a comparison of the evaporative, refueling, and tailpipe emission estimates from gasoline LDVs.

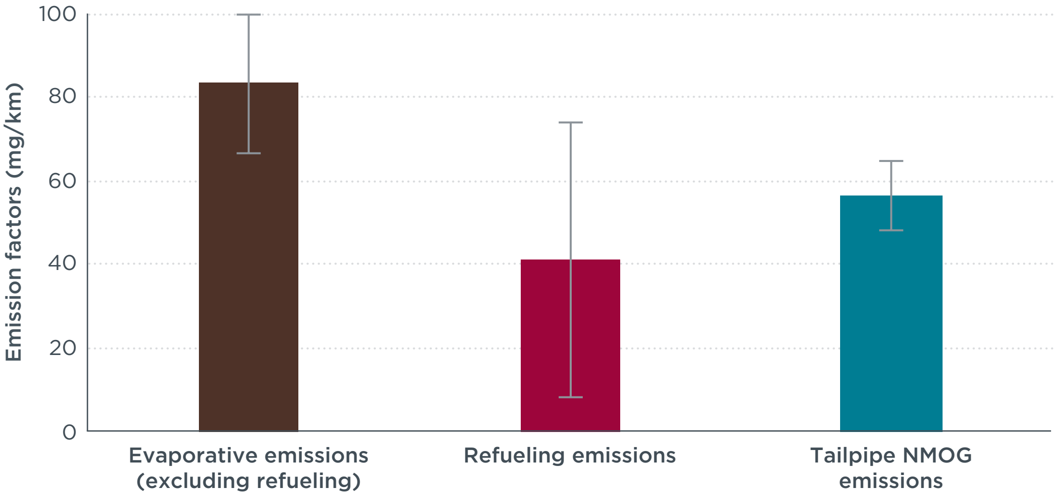

Figure 7. Evaporative, refueling, and tailpipe emission factors for European gasoline vehicles. Error bars represent the expected range for typical vehicles.

The annual evaporative emissions, excluding refueling, from typical European gasoline cars have been estimated at approximately 1000 grams per vehicle.[68] Using the typical annual mileage of passenger vehicles, this estimate translates to be approximately 80 mg/km, which is roughly 50% higher than the tailpipe emission factors for Euro 6 gasoline vehicles.[69]

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[68] Theodoros Grigoratos, Giorgio Martini, and Massimo Carriero, “An experimental study to investigate typical temperature conditions in fuel tanks of European vehicles,” *Environmental Science and Pollution Research,* 2019, 26 (17): 17608–17622, https://doi.org/10.1007/s11356-019-04985-7.

[69] European Environment Agency, “Passenger cars, light commercial trucks, heavy-duty vehicles including buses and motor cycles.”

The refueling emission factors are highly sensitive to the efficiency of the Stage II vapor recovery systems installed at European service stations. In Stage II systems the vapors displaced from the vehicle's tank are returned to the service station's tank via special fittings in the dispensing nozzle. However, the in-use efficiency of such systems varies, resulting in the wide range depicted by the errors bars in Figure 7. For poorly maintained Stage II systems, refueling emissions are in the same order of magnitude as tailpipe HC emissions.

The primary technology used to control evaporative emissions from motor vehicles is the carbon canister. Highly adsorbent activated carbon particles, housed within the canister, trap fuel vapors that would otherwise have to be emitted to the atmosphere. Carbon canisters allow these fuel vapors to be used in engine combustion as the canister is purged during driving. Two main parameters influence the effectiveness of carbon canisters: the volume and the purging rate. Larger canisters accommodate greater amounts of activated carbon and trap more fuel vapor before becoming saturated. The purging rate determines how quickly trapped vapors are consumed by the combustion engine during canister regeneration. Generally, the canister size and purging strategies are designed to meet certification test requirements. Thus, more challenging test procedures and stricter emission limits force better designs of the evaporative emission control systems. Recent research[70] suggests that the size and purging strategy of evaporative emissions systems mounted on European passenger cars are not effective under real-world use.

Current regulation

The evaporative emissions requirements recently were improved in the amendments introduced by the WLTP Second Act. However, the test limit was maintained at 2 grams per test; that is, the same limit established in 1991 for Euro 1. Compared to the previous legislation from 1998,[71] the new evaporative emissions test protocol extends the duration of the diurnal loss test from 24 to 48 hours; reduces the conditioning driving duration, which is used for canister purging prior to the diurnal test; includes an additional multi-week test to determine the permeability losses of the fuel tank system; and sets provisions to ensure the canisters used in testing have been aged. The evaporative emissions performance must now be demonstrated in-use, and a test can be carried out up to 5 years or 100,000 km. The test fuel is the same used in the rest of the type-approval tests, namely E10. Flex-fuel and dual fuel vehicles must only demonstrate compliance using E10.

In Europe, refueling emissions are controlled using Stage II systems installed on pumps at fuel dispensing stations. In 2009, an EU directive[72] was adopted mandating the installation of Stage II systems at service stations with a vapor capture efficiency of at least 85%. However, Stage II systems require periodic maintenance to ensure this vapor

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[70] Michele De Gennaro, Elena Paffumi, and Giorgio Martini, "Data-driven analysis of the effectiveness of evaporative emissions control systems of passenger cars in real world use condition: Time and spatial mapping," *Atmospheric Environment,* 2016,129: 277–293, https://doi.org/10.1016/j.atmosenv.2016.01.026.

[71] Parliament and Council of the European Union, "Directive 98/69/EC of the European Parliament and of the Council of 13 October 1998 Relating to Measures to Be Taken against Air Pollution by Emissions from Motor Vehicles and Amending Council Directive 70/220/EEC," *Official Journal of the European Union* L 350 (December 28, 1998), http://data.europa.eu/eli/dir/1998/69/oj.

[72] Parliament and Council of the European Union, "Directive 2009/126/EC of the European Parliament and of the Council of 21 October 2009 on Stage II Petrol Vapour Recovery during Refuelling of Motor Vehicles at Service Stations," *Official Journal of the European Union* L 285 (October 31, 2009), http://data.europa.eu/eli/dir/2009/126/oj.

capture efficiency. Lower efficiencies are expected due to the limited monitoring and enforcement of Stage II systems.[73]

International comparison

The evaporative emission standards in the United States are the most comprehensive and include tests and limits to account not only for hot-soak and diurnal evaporative emissions, as in the EU requirements, but also for running losses and refueling emissions. Although a separate permeability test does not exist, the strict diurnal and leak limits force manufacturers to use low permeation materials.

Table 3 summarizes the U.S. Tier 3 evaporative emission tests and applicable limits. The evaporative performance must be demonstrated up to 15 years or 240,000 km.

Table 3. U.S. Tier 3 evaporative emissions tests and limits for gasoline light-duty vehicles

Test	Limit	Notes
High temperature hot-soak + 3-day diurnal test	0.3 and 0.65 g/test (low/high altitude)	The 3-day test captures all sources of evaporative emissions and ensures that the canister is large enough to capture diurnal emissions. The hot-soak is performed after the running losses test, at 32°C to 38°C.
	0.65 g/test (high altitude)	
Hot-soak + 2-day diurnal test	0.3 g/test (low altitude)	The 2-day test ensures that the purge rate is enough to empty a full canister. To do so, the hot-soak, at 20°C to 30°C, is performed right after a hot-started test on the chassis dynamometer.
	0.65 g/test (high altitude)	
Canister bleed test	0.020 g/test	This procedure quantifies diurnal emissions without measuring hot-soak emissions. It measures 2 days of diurnal emissions from just the tank and the canister.
Running losses test	0.031 g/km	The test is performed over a sequence of idling, and the UDDS and New York City Cycle. The test temperature is 35°C (32.2°C for high altitude test).
Refueling test	0.053 g/liter of fuel dispensed	Assesses the onboard refueling vapor recovery (ORVR) for control of refueling emissions. Corresponds to 95% vapor capturing efficiency.
Spit back test	1 g/test	Spit back emissions result from loss of liquid fuel during refueling. Fuel is dispensed at 37 L/min.
Leak test	0.5 mm equivalent diameter	The cumulative equivalent diameter of leak orifices in the system cannot be exceeded. Focus on in-use.
OBD EVAP monitors	0.5 mm equivalent diameter	OBD system must find leaks larger than 0.020 inches cumulative equivalent diameter and notify the owner.

The Tier 3 limits aim to achieve essentially zero fuel vapor emissions. The level of the standards is set to accommodate the background hydrocarbon emissions resulting from the off-gassing of volatile hydrocarbons from polymers found in new vehicles (e.g., tires, interiors, seats, paints, adhesives).

The evaporative emission standards in China and Brazil are also more stringent than the European requirements. The China 6 standard has a tighter evaporative emission limit (0.7 g/test) over the 2-day diurnal emission test with hot-soak and also mandates a higher conditioning temperature (38 ± 2°C) prior to the test. In addition, China 6 also adopted a refueling emission limit of 0.05 g/L. This provision forces the introduction of onboard refueling vapor recovery (ORVR) systems. A combined Stage II and ORVR

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[73] Freda Fung and Bob Maxwell, "Onboard refueling vapor recovery: Evaluation of the ORVR program in the United States" (ICCT: Washington DC, 2011), https://www.theicct.org/sites/default/files/publications/ORVR_v4.pdf.

program was deemed a comprehensive solution providing both short-term and long-term benefits.[74]

Brazil's PROCONVE L7 sets an evaporative emission limit of 0.5 g/test over the 2-day diurnal emission test and introduces a refueling emission limit of 0.05 g/L. The 2-day diurnal and refueling testing procedures are the same as in the United States.

In the United States, Stage II systems were required in polluted cities and are still required in California. However, due to the wide deployment of ORVR systems as required by the refueling standards, Stage II is no longer considered a cost-effective solution for addressing refueling emissions.[75]

Recommendations

Although the changes introduced by the WLTP Second Act represent notable improvements with respect to the previous regulation, the new EU evaporative emissions requirements are still the most lenient when compared to provisions in the United States, China, and Brazil**.** We offer the following recommendations:

» **Tighten the evaporative emissions limit**. The current limit of 2 grams per test was established in 1991 for Euro 1. The Tier 3 limit in the United States is 85% lower than the current limit in the EU for the 2-day diurnal test. Adoption of tighter limits will drive the adoption of larger canisters and of more effective purging strategies.

» **Introduce a refueling emissions standard.** Capturing emissions during refueling by the vehicle's canister is more effective than the current Stage II controls and avoids problems with Stage II system malfunctions. Experience in the United States and China shows that ORVR has a higher capture efficiency than Stage II and does not have the drawbacks, such as sensitivity to fuel composition, continuous maintenance and inspection requirements, or higher cost. Furthermore, the larger canister required by the ORVR system benefits diurnal emissions beyond the requirements of the 2-day test. The average cost to implement ORVR in European vehicles is approximately 25 euros per vehicle.[76]

» **Increase the temperature during hot-soak prior to the 2-day diurnal test.** The EU hot-soak test must be performed between 23°C and 31°C. Due to the temperature anomaly caused by global warming, temperatures above 31°C are more frequently experienced in many European regions during summer. Increasing the conditioning and hot-soak temperature would not only improve the representativeness of the test, but would also introduce the need for adequate thermal management of the tank without mandating a running losses test. This is the approach followed in the China 6 standards. UNECE's global technical regulation (GTR) 19, which defines the evaporative testing protocol, would need to be amended in this case to allow countries to define different soak temperatures.

» **Introduce requirements for the monitoring of leaks in the OBD provisions.** OBD monitors are a cost-effective solution to improve the durability of evaporative emissions systems, and a useful tool for compliance programs. OBD leak monitoring has been required in the United States since the Tier 1 standards, in 1996.

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[74] Xiaofan Yang et al., "Vehicular volatile organic compounds losses due to refueling and diurnal process in China: 2010-2050," *Journal of Environmental Sciences,* 2015, 33: 88–96, https://doi.org/10.1016/j.jes.2015.01.012.

[75] Fung and Maxwell, "Onboard refueling vapor recovery: Evaluation of the ORVR program in the United States."

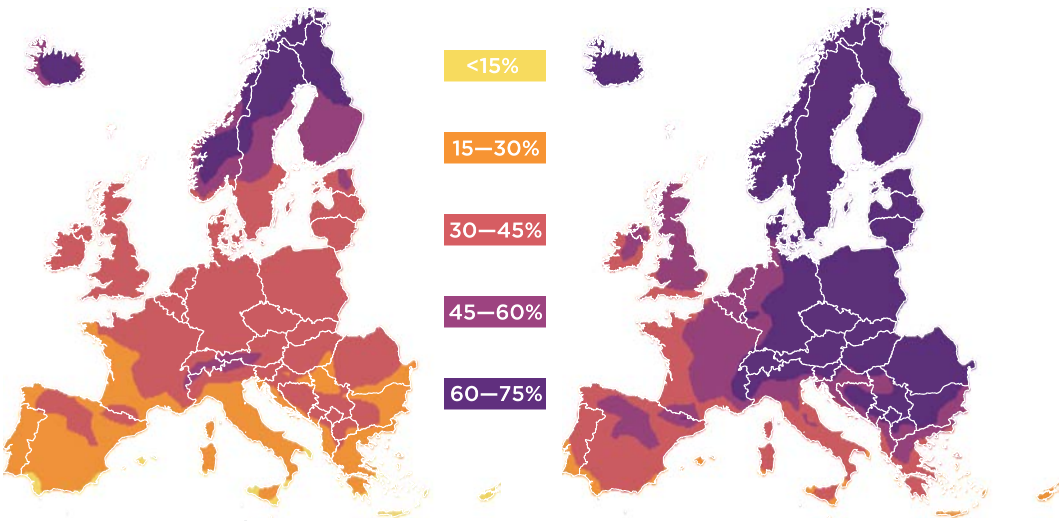
[76] Personal communication with a European manufacturer of EVAP control systems.

LOW TEMPERATURE TEST

What is the issue?

The link between low ambient temperatures and higher emissions has been robustly established by a plurality of studies of both diesel and gasoline engines, as well as of regulated and unregulated pollutants.[77] The higher emissions are a result of engine rapid warm-up strategies, poorly designed emission control systems, and auxiliary emission control strategies that deactivate emission controls at low temperatures.

A recent study[78] quantified the impact of low ambient temperature on the NO_x emission of diesel vehicles. As shown in Figure 8 some regions experience up to 75% greater NO_x emissions during winter, compared to the NO_x emissions measured during the type-approval test at standard temperatures. Neither NO_x emissions nor diesel vehicles are currently regulated by the low temperature laboratory test.



Increase in diesel NO_x emissions due to deviations in ambient temperature from the temperature used for type-approval laboratory testing

Mean annual temperature **Winter average temperature**

Figure 8. Increase in diesel NO_x emissions in Europe due to temperatures lower than 20°C based on remote sensing data acquired during 2017 and 2018. Adapted from Grange et al. (2019).

The current low temperature emissions regulation has not seen changes since it was introduced with the Euro 3 standards. The low temperature test was developed in a time when catalytic emission control systems existed only for spark ignition engines. Therefore, the standard covers only HC and CO emissions of gasoline engines. Diesel cars are fully exempted from the test.

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[77] Ricardo Suarez-Bertoa and Covadonga Astorga, “Impact of cold temperature on Euro 6 passenger car emissions,” *Environmental Pollution,* 2018, 234: 318–29, https://doi.org/10.1016/j.envpol.2017.10.096.

[78] Stuart K. Grange et al., “Strong temperature dependence for light-duty diesel vehicle NO_x emissions,” *Environmental Science & Technology*, 2019, 53 (11): 6587–6596, https://doi.org/10.1021/acs.est.9b01024.

Current regulation

The current low temperature laboratory test and the respective limits were introduced more than 20 years ago by Directive 98/69/EC. The low temperature test procedure, conducted at -7°C, uses the urban portion of the New European Driving Cycle (NEDC) test. The regulation sets HC and CO limits for gasoline vehicles of 15 g/km and 1.8 g/km respectively. That is, the limits are 15 and 18 times the Euro 6 emissions limit for the type-approval test at standard temperature (see Table 2).

As previously stated, under the current regulations the low temperature test is not required to be conducted on diesel vehicles. However, since Euro 5, manufacturers must demonstrate that the emission control system is warm enough for efficient operation within 400 seconds after a -7°C cold start.

A new low temperature procedure is being developed in the context the UNECE's World Forum for Harmonization of Vehicle Regulations.

International comparison

Low temperature tests in the United States and China share some elements with the EU procedure; they are also performed at -7°C and have the same dynamometer correction provisions to reflect the higher road load at low temperature. However, the low temperature procedure in those countries covers both gasoline and diesel vehicles. Furthermore, the latest pollutant standards in China set the world's first limits for NO_x emissions in the low temperature test. Table 4 shows the low temperature emission limits for Euro 6, U.S. Tier 3, and China 6. The emission limits cannot be compared directly because of the differences among test cycles.

Table 4. Low temperature limits and cycles in the European Union, United States, and China

	CO (g/km)	HC (g/km)	NO_x (g/km)	Test cycle	Notes
Euro 6	15	1.8 (THC)	-	NEDC, urban portion	Applies only to gasoline.
U.S. Tier 3	6.2	0.19 (NMHC)	-	FTP-75	Applies to gasoline and diesel. Heater and defroster must be on.
China 6	10	1.2 (THC)	0.25	WLTC, low and medium phases	Applies to gasoline and diesel.

Recommendations

The boundary conditions of in-service conformity RDE testing allow for testing at temperatures down to -7°C in the extended boundary conditions. However, RDE low temperature testing is not a replacement for low temperature chassis dynamometer testing for type approval. The weather conditions and time slots for low temperature RDE testing can be short and unpredictable, and do not capture all type-approved vehicles. Moreover, the fraction of cold-start driving during an RDE test is small compared to the average duration of the urban portion of an RDE test; low temperature emissions are better assessed in shorter cycles. Lastly, RDE limits currently cover just two pollutants, NO_x and PN.

A new low ambient temperature test and new emission limits covering a wider range of pollutants need to be defined. We offer the following recommendations:

- **Low temperature emission limits should be technology-neutral.** Modern diesel engines rely on catalytic aftertreatment systems to meet emission limits and are therefore significantly affected by low temperatures. Future low temperature emission limits should apply to all engine types regardless of fuel and ignition or injection technology.
- **Set low temperature limits for a wider set of pollutant emissions.** Current limits focus only on CO and HC emissions. However, recent research by the JRC[79] has shown that the emissions of NO_x, PN, and ammonia also increase significantly at low temperatures. The set of pollutants regulated by the low temperature test should mirror those regulated at ambient temperatures.
- **Tighten the current low temperature limits.** The current low temperature limits for CO and HC emissions were introduced more than two decades ago. The current HC and CO limits, which are set at over 15 times the Euro 6 emissions limit, must be revised in future emissions legislation.
- **Develop a new low temperature test procedure.** The current test procedure uses the urban portion of the NEDC cycle and is not representative of real-world operation. It is recommended to move toward a definition based on the Worldwide Harmonized Light Vehicles Test Cycle (WLTC). Furthermore, the use of heating and defrosting systems should be mandated during the test.
- **Monitor the greenhouse gas emissions over the low temperature test.** Low temperatures also have a significant effect on the CO_2, N_2O, and CH_4 emissions of motor vehicles. The emissions of these GHGs should be measured and monitored over the low temperature test, enabling their inclusion in future GHG standards.

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[79] Suarez-Bertoa and Astorga, “Impact of cold temperature on Euro 6 passenger car emissions.”

ON-ROAD CO EMISSIONS FROM GASOLINE VEHICLES

What is the issue?

Road transport is responsible for approximately 20% of all CO emissions in the EU. CO is one of the precursors of tropospheric ozone, which in 2015 was responsible for 16,400 premature deaths in the EU.[80]

CO emissions are primarily the result of over fueling, also called fuel enrichment. During enrichment, there is not enough oxygen to fully oxidize the fuel to form CO_2. The excess fuel is then only partially oxidized to form CO. During fuel rich conditions, the catalyst conversion efficiency is also severely compromised, and the engine-out CO emissions cannot be controlled.

Enrichment in modern fuel-injected gasoline engines is normally encountered only during cold engine starts, especially at cold ambient temperatures; during high engine loads; or as the result of an emission control system malfunction. An analysis done by the European Commission's JRC shows that approximately 10% of Euro 6b gasoline vehicles in the RDE monitoring dataset and other publicly available sources exhibited CO emissions above the Euro 6 limits (see Figure 9).[81]

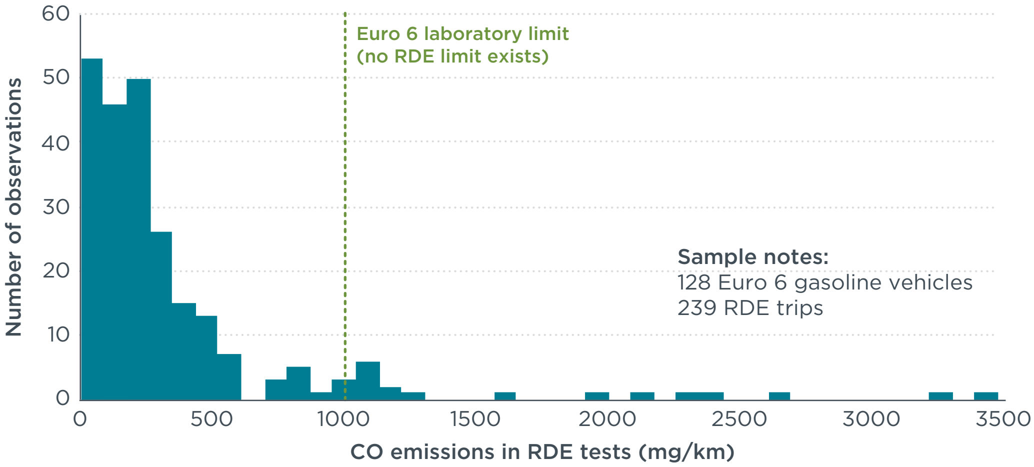

Figure 9. RDE CO emissions of Euro 6 vehicles in the RDE monitoring database. Adapted from the Joint Research Centre (2019).

For some vehicles, CO emissions over the complete route are higher than over the urban part, suggesting that the CO emissions do not originate in cold-start, but in the warmed-up motorway section.[82] A recent JRC study[83] reported very high CO emissions for several gasoline vehicles during on-road tests that were dynamically driven. The emission levels

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[80] European Environment Agency, *Air Quality in Europe — 2018 Report*.

[81] Joint Research Centre, "EMROAD and RDE-LDV golden data set," in *CIRCABC: Internal Market, Industry, Entrepreneurship and SME's, New Light Duty Test Procedures*, 2019, https://circabc.europa.eu/webdav/CircaBC/GROW/wltp/Library/RDE-LDV/Margin%20Review/Margin%20Review%202019/12%20April%202019%20Meeting/20190412_PEMS_zero_drift_assessmentV4.pdf.

[82] M. Clairotte et al., "Joint Research Centre 2017 light-duty vehicles emissions testing contribution to the EU market surveillance: Testing protocols and vehicle emissions performance." (Joint Research Centre of the European Commission, 2018), https://ec.europa.eu/jrc/en/publication/joint-research-centre-2017-light-duty-vehicles-emissions-testing.

[83] Suarez-Bertoa et al., "On-road emissions of passenger cars beyond the boundary conditions of the real-driving emissions Test."

reached 7,500 mg/km, more than 7 times higher than the already lenient Euro 6 limit of 1,000 mg/km. On-road CO emissions from diesel vehicles were generally well below the Euro 6 diesel limit of 500 mg/km, even under dynamic driving. Thus, diesel CO emissions are not of concern.

Fuel consumption standards have incentivized the downsizing of engines. As gasoline engines get downsized, they operate more frequently in areas of the engine map that result in high-temperature exhaust gases. To avoid abnormal combustion phenomena caused by these high temperatures, and to protect the engine and aftertreatment components from the flow of overly hot exhaust gases, one approach is to cool down the combustion process through fuel enrichment. Rich operation can also be used to increase engine power output, especially as a way to increase the boost from turbocharged engines. However, this leads to incomplete combustion and high engine-out CO emissions, which a three-way catalyst (TWC) cannot control.[84]

Technologies and operational strategies do exist, however, that can achieve ultra-low CO emissions in real driving scenarios, while at the same time ensuring the protection of engine components. These include, among others, cooled exhaust manifolds, advanced turbocharger materials enabling exhaust gas temperature up to 1050°C, injection of water to cool the combustion process, use of variable compression ratio to reduce knock and spark retard at high loads, and electric turbochargers that reduce the exhaust temperature through lower backpressures and residual gas fractions.[85]

Current regulation

As of September 2017,[86] newly type-approved vehicles must comply with emission limits measured over the on-road RDE test. The RDE regulation establishes not-to-exceed limits for NO_x and PN emissions, based on the Euro 6 limits and a set of conformity factors. While CO emissions must be measured and recorded during each RDE test, they are not bound by a not-to-exceed limit. That is, no conformity factor (CF) exists for CO in the RDE regulation.

Fuel enrichment for component protection can fall into one of the allowed uses of auxiliary emission strategies (AES), and would potentially not constitute a defeat device. Even if a manufacturer's inadequate design or inferior technology selection is the reason fuel enrichment is needed, type-approval authorities will continue to have the legal grounds to allow it as a valid AES.

The current legislation does not provide sufficient regulatory pull to incentivize the widespread adoption of technologies for reducing or eliminating fuel enrichment.

International comparison

Until now, Brazil is the only region to set conformity factors for CO for RDE tests. A CO conformity factor of 2 applies from 2025, with the introduction of PROCONVE L8. The CF is adjusted to 1.5 two years later.[87] The China 6 standards only require for CO to be

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[84] Yoann Bernard, “Fighting fire with Fuel: Why the EU Should cap the level of fuel enrichment in passenger car engines,” *International Council on Clean Transportation* (blog), June 24, 2019, https://theicct.org/blog/staff/fighting-fire-with-fuel.

[85] Michael Görgen et al., “New lambda = 1 gasoline powertrains new technologies and their interaction with connected and autonomous driving” (30th International AVL Conference “Engine & Environment,” Graz, Austria, 2018), https://www.avl.com/documents/10138/8682805/14+Baumgarten.pdf.

[86] European Commission, “Regulation (EU) 2017/1151.”

[87] Ministério do Meio Ambiente and Conselho Nacional do Meio Ambiente, “RESOLUÇÃO Nº 492,” Article 22.

measured and recorded during RDE tests. However, for China 6b, the laboratory CO limits for gasoline engines were brought down to 500 mg/km.

To address the pollutant emissions resulting from excessive enrichment from AES, the U.S. Tier 3 standards introduced[88] limitations on the enrichment level over the US06 and SC03 certification cycles. To limit excessive enrichment, the U.S. Tier 3 standards mandate that the nominal air-fuel ratio cannot be richer at any time than the leanest air-fuel ratio required to obtain maximum torque. To account for in-use variance, a tolerance of 4% is allowed during vehicle testing. Although this value is expected to vary from engine to engine, the enrichment limit corresponds to circa 10% to 15% richer than stoichiometric operation. Additional enrichment for thermal protection is allowed, but only after a burdensome reporting and evaluation by the U.S. Environmental Protection Agency, including meticulous documentation proving that the need for enrichment does not stem from the use of inferior technology.

As a result, U.S. manufacturers are expected to deploy technologies to manage knock, peak combustion temperatures, and exhaust temperatures during high-load operation without relying exclusively upon fuel enrichment.

Recommendations

The real-world CO emissions of gasoline power trains should receive greater attention. Due to the clear link between CO emissions, cold start, and dynamic driving, the following recommendations are only one element to tackle on-road CO emissions. Extending the dynamic boundaries for RDE testing and the allowed temperature window for testing is also necessary. These boundary conditions are addressed in the two following sections.

We offer the following recommendations:

» **Introduce not-to-exceed limits for CO during RDE testing**. The inclusion of CO into the RDE regulatory framework is a necessary step to limit the high CO emissions of gasoline vehicles observed in the motorway section of RDE trips. An RDE conformity factor for CO must be developed. Results by the JRC[89] comparing PEMS and laboratory measurements suggest that the PEMS measurement uncertainty for CO is even lower than for other pollutants, at approximately 100 mg/km. Compared to the current Euro 6 limits, this represents a conformity factor between 1.1 and 1.2.

» **Reduce the laboratory limit for CO.** The Euro 6 limit for gasoline CO emissions is the same as Euro 4 standards, which were implemented in 2000, and should be revised and reduced to at least the same level required for diesel engines in the future Euro standards.

» **Introduce limitations for fuel enrichment as an auxiliary emissions strategy**. Technologies exist to ensure the protection of engine and aftertreatment components from high temperatures without the need for fuel enrichment. The U.S. Tier 3 standards set limits to fuel enrichment over the certification cycles and request a detailed report of the need of it for thermal management. These could be replicated in the EU to limit the enrichment resulting from auxiliary emissions strategies.

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[88] U.S. EPA, "Control of Air Pollution From Motor Vehicles: Tier 3 Motor Vehicle Emission and Fuel Standards," 23458.

[89] Joint Research Centre, EMROAD and RDE-LDV Golden Data Set.

BOUNDARY CONDITIONS FOR RDE TESTING

What is the issue?

Even though RDE tests are conducted on public roads open to traffic, the regulatory provisions limit the range of driving conditions under which testing can take place. The intent when selecting said limits was to cover 95% of the full range of normal use. However, the combined application of the different boundary conditions results in much less than 95% of all driving conditions covered by RDE testing, as noted in a study by TNO, a Dutch research organization.[90]

Boundary conditions exist for the payload, altitude, cumulative altitude gain, ambient temperature, trip composition, maximum speed, and driving dynamics. The latter are quantified using the product of the vehicle speed with its positive acceleration (v*a) for the upper boundary, and of the relative positive acceleration (RPA) for the lower boundary. Figure 10 shows the driving dynamic boundary conditions and compares them to dynamometer cycles used for type approval in the EU and the United States. The current boundary conditions would render invalid the NEDC cycle, because of its dynamicity being too low, as well as the US06 cycle due to its dynamicity being too high. A recent study by the European Commission[91] shows significantly higher emissions when on-road tests are performed outside the dynamic boundary conditions.

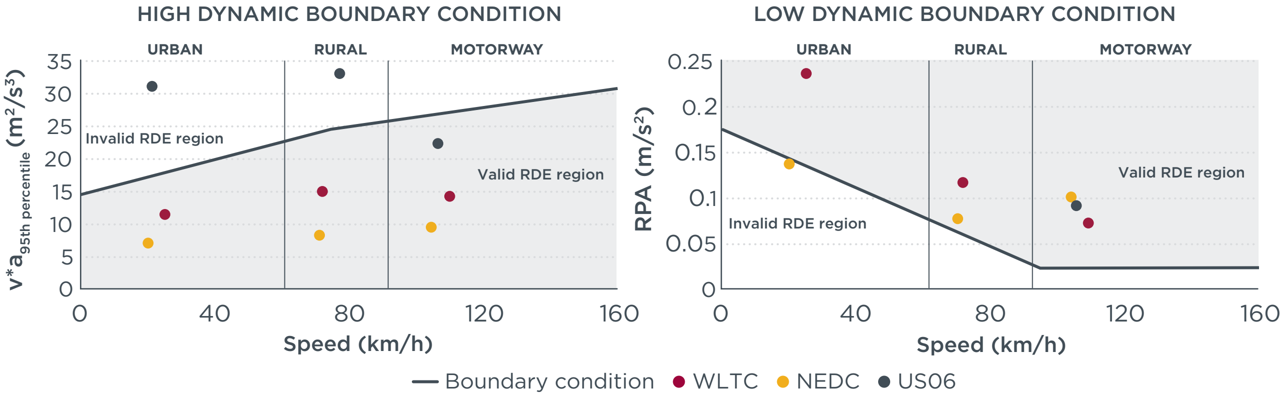

Figure 10. Dynamic boundary conditions compared to three dynamometer driving cycles.

Measurements by the French research organization IFPEN, including more than 86,000 trips and close to 2 million driven kilometers in real-world conditions in France, show that the dynamic boundary conditions cover only 90% of all driving conditions in rural and highway operation, and not 95% as originally intended.[92] This proportion is expected to be even lower for European countries where the average vehicle power is higher than in France,[93] such as in Germany or the United Kingdom. Vehicles with high power-to-

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[90] P. van Mensch, R. F. A. Cuelenaere, and N. E. Ligterink, *Assessment of Risks for Elevated NO_x Emissions of Diesel Vehicles Outside the Boundaries of RDE. Identifying Relevant Driving and Vehicle Conditions and Possible Abatement Measures*, (TNO, 2017), https://repository.tudelft.nl/view/tno/uuid:b0ff9bd6-41d0-4d88-89fe-012321e955be.

[91] Suarez-Bertoa et al., "On-road emissions of passenger cars beyond the boundary conditions of the real-drivingeEmissions Test."

[92] IFP Energies nouvelles, "IFPEN Geco Air," 2017, https://circabc.europa.eu/sd/a/95c1b9a5-b7df-411d-9db4-88d5ebb2e536/20171023_IFPEN_Geco_air_Short_presentation.pdf.

[93] ICCT, "European vehicle market statistics—Pocketbook 2018/2019" (The International Council on Clean Transportation, 2018), https://www.theicct.org/publications/european-vehicle-market-statistics-20182019.

weight ratios would not have the regions of the engine map close to the full load curve, which are usually challenging for pollutant emissions control, thoroughly scrutinized. Lastly, because of the potential for invalid tests, RDE tests likely will not be performed close to the dynamic boundary conditions, further reducing the representativeness of RDE tests.

The same dataset by IFPEN shows that more than 12% of the trips are outside of the boundary conditions on cumulative altitude gain, currently set at 1,200 m of elevation gain for every 100 km. Based on this large dataset for France, shown in Figure 11, to capture 95% of the driving situations the boundary condition should be set to at least 1,800 m per 100 km, and this is expected to be higher for European countries with more mountainous topography such as Austria, Greece, Italy, Spain, Switzerland, and Norway.

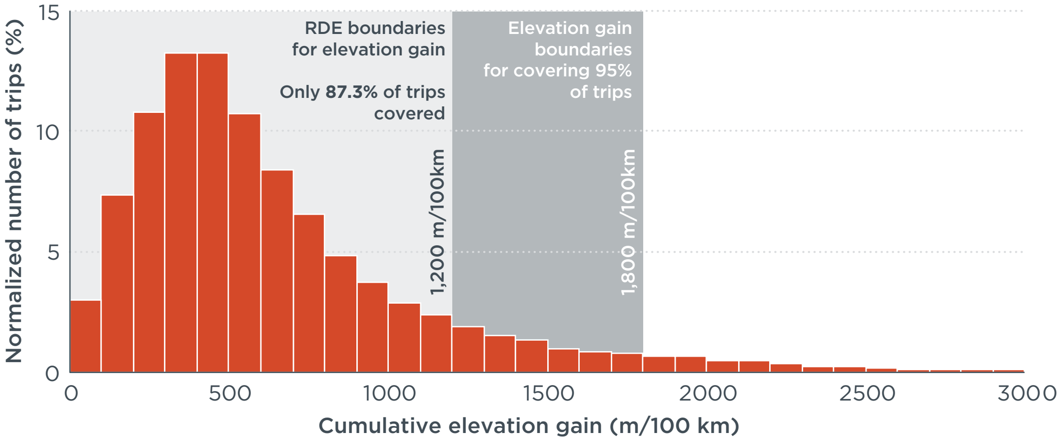

Figure 11. Measured cumulative elevation gain from more than 86,000 trips in France. Adapted from IFP Energies Nouvelles (2017).

The current temperature boundary conditions establish two ranges in which RDE tests can be conducted: a moderate range from 0°C to 30°C, and an extended range from -7°C to 35°C. In the extended temperature range, the reported vehicle emissions are adjusted downward through the use of a multiplier, and emissions are allowed to be 60% higher than the limits set for the moderate temperature range. These temperature ranges were negotiated by policymakers and are not based on surface temperature measurements, nor do they take into account the temperature anomalies caused by climate change that increase the frequency of cold spells during winter and heat waves during summer. Furthermore, the correction factor used to underreport emissions on the extended temperature range is not based on a technology feasibility assessment. Most importantly, in properly designed emission control systems, there is no technical justification for higher emissions in hot weather.

A further constraint is placed on the validity of RDE trips by the required trip composition and associated average speed requirements. RDE trips cover three types of operation that should be performed in the following order: urban, rural, and motorway. Figure 12 shows the possible combinations of distance and average speed in the urban section for a valid RDE trip. Because of the trip composition requirements, the minimum distance in the speed range of typical urban driving, circa 30 km/h, is more than 20 km long. RDE data submitted by manufacturers show that the average distance of the urban section is 33 km.[94] A study by the Technical University Dresden on mobility in German cities[95] reveals that many real-world vehicle trips are significantly shorter than that. On average, such a trip has a length of 10–11 km, driven at an average speed of 28–33 km/h. That is, the typical German city trip falls entirely outside the RDE region of validity for urban trips.

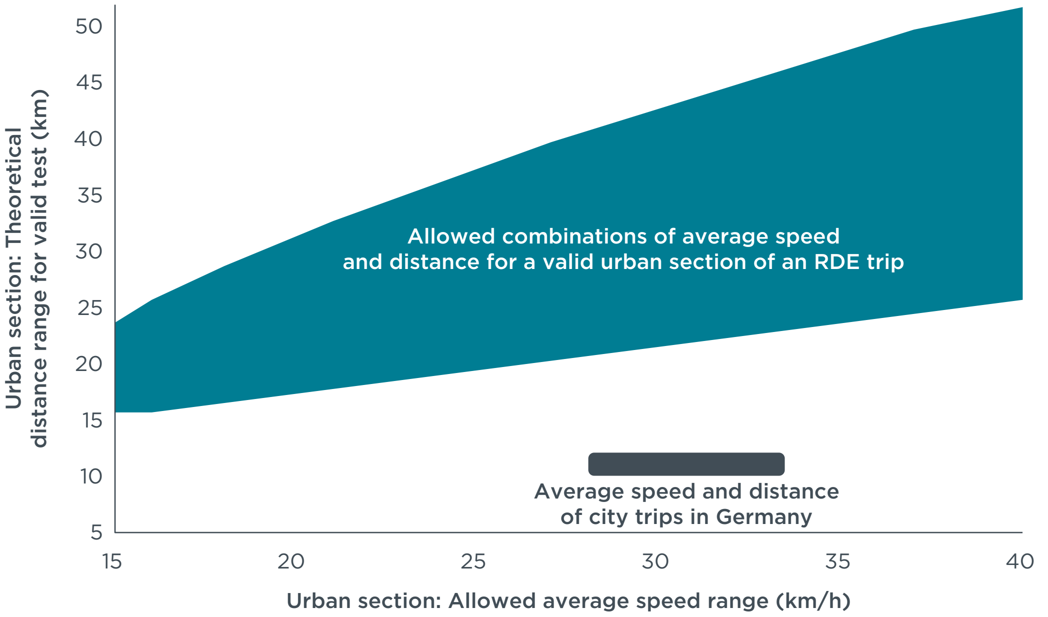

Figure 12. Valid RDE range of urban distance and speed versus the average German city trip.

A significant portion of motor vehicle emissions occur during cold-start. This is the period between turning on the vehicle and when the engine and aftertreatment system have reached their operational temperature, defined in the regulation as 70°C. This period varies from vehicle to vehicle, but it is limited to the first few minutes and kilometers of operation. The long urban trip distances required by the current RDE provisions mean the contribution of cold-start emissions to the total RDE urban trip is lower than in the real world. In other words, the urban emissions as calculated by the RDE methodology will not be representative of the actual urban emissions occurring in European cities.

The tacit guiding principle when designing the RDE regulation was to cover 95% of real-world conditions. However, each of the RDE boundary conditions presented above excludes more than 5% of driving conditions. Moreover, the combination of all individual boundary conditions means that substantially less than 95% of all driving situations will be within the RDE boundaries.

Current regulation

The current applicable RDE boundary conditions are listed in the consolidated version of Regulation (EU) 2017/1151, including all RDE amendments. The limits imposed by the

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[94] ICCT analysis of RDE monitoring database (n.d.)

[95] Gerd-Axel Ahrens, “Forschungsprojekt „Mobilität in Städten – SrV 2013“” (TU Dresden, October 2014), https://tu-dresden.de/bu/verkehr/ivs/srv/srv-2013.

regulation that are relevant for the following recommendations are shown in Figure 10 through Figure 12.

International comparison

The European Union has been leading the development of the RDE regulatory framework. The RDE procedure, developed by the European Commission, has now been adopted by UNECE's Working Party on Pollution and Energy (GRPE). China, South Korea, Japan, India, and Brazil have adopted RDE requirements in their emissions legislation. Although the regions mimic the European RDE provisions, they include modifications addressing the unique driving conditions in their respective territories. For example, China's regulation allows testing up to 2,400 m of altitude and South Korea's covers only diesel vehicles. The regulations in Japan and India cover lower driving speeds and higher temperatures, and Brazil's regulations include RDE limits for CO and NMHC.

Recommendations

Limitations placed by the RDE boundary conditions effectively cover far less than 95% of all driving conditions, the stated intent during the development of the regulation. We offer the following recommendations:

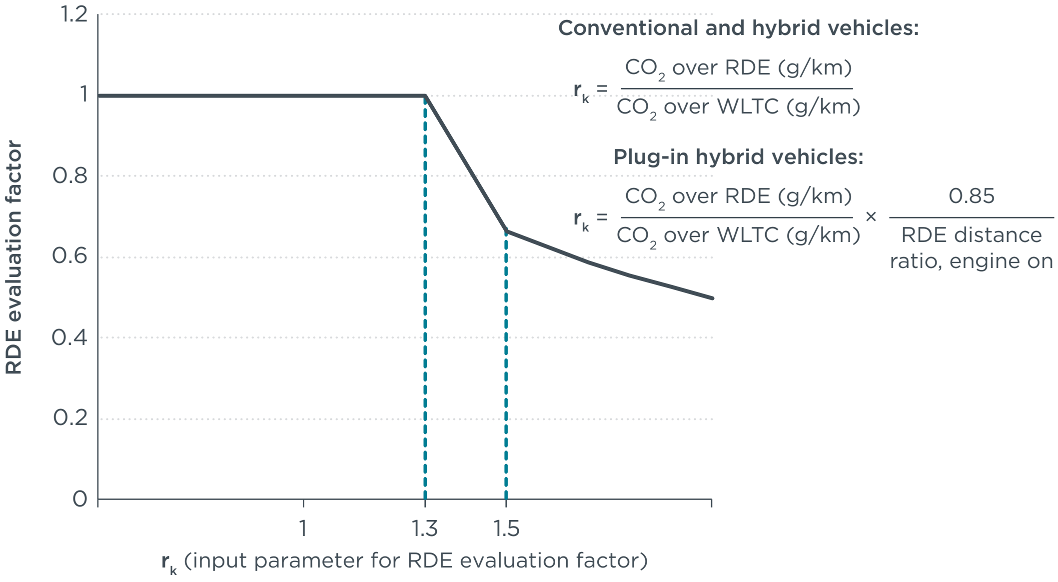
- **Extend the upper boundary conditions for RDE driving dynamics.** The current upper boundary for driving dynamics can render invalid a large portion of driving situations. The upper boundary makes RDE trips less dynamic than the US06 cycle, a dynamometer driving cycle used in the United States for emissions certification. The current provisions limit the scrutiny of high-powered vehicles in operating points close to the full load curve.
- **Eliminate the lower boundary condition for RDE driving dynamics.** The current lower boundary for driving dynamics renders invalid the NEDC dynamometer driving cycle used for type approval in the past decades. The RPA lower limit should be eliminated to allow RDE tests with low dynamicity, as it is encouraged by vehicle user interfaces aimed at saving fuel.
- **Revise the speed regimes for rural and motorway driving and eliminate the high-speed limit during RDE tests.** The speed limit on rural roads of some Member States is 100 km/h but the regulation defines all driving above 90 km/h as motorway driving. Furthermore, RDE provisions should not set limits on the maximum test speed, as these are determined by the road speed limits in force at the test location.
- **Extend the cumulative elevation gain boundary condition.** Available data suggest that to cover 95% of driving conditions, the elevation gain boundary limit needs to be substantially increased from the current 1,200 m per 100 km.
- **Extend the temperature range of the moderate boundary conditions, eliminate the limits for the extended boundary conditions, and revise the extended boundary conditions correction factor.** The temperature ranges should be based on surface temperature data, aiming to cover 95% of driving situations, and taking into account the observed temperature anomalies brought by climate change. Furthermore, the 1.6 correction used for under-reporting emissions in the extended boundary conditions should be revised.

- **Adjust trip requirements to allow shorter urban sections and extend the cold-start boundary conditions.** With the current trip requirements, a valid RDE urban trip conducted at an average speed of 30 km/h, typical of city driving, would be at least two times longer than the trips observed in many European cities. To better capture the cold-start urban emissions, the methodology needs to be modified to capture shorter urban trips. Furthermore, the trip limitations during the cold-start phase should be removed. In highly congested areas, mean speeds below 15 km/h are common; in rural areas, speeds higher than 60 km/h before the coolant reaches 70°C are likely.
- **Remove boundary conditions that reveal that an RDE test is taking place.** Boundary conditions such as the maximum trip duration; the test order of urban, rural and motorway trips; the duration limits for vehicle soaking; and the limitation that tests cannot be performed Saturdays, Sundays, and holidays do not have a technical foundation and simplify the detection that an RDE tests is being performed. These conditions should be eliminated.

RDE EMISSIONS EVALUATION METHOD

What is the issue?

The values used to determine compliance in an RDE test are not the emissions actually measured. Raw emissions are adjusted downward by the so-called *RDE evaluation factor*. This factor, used to underreport the pollutant emissions measured over the complete RDE trip, is a function of the CO_2 emissions over the RDE test, the declared CO_2 over the WLTC test (used as a reference value), and of the trip share driven with the engine on in the case of plug-in hybrids. Figure 13 shows how the RDE evaluation factor is calculated. The Commission's intent in using such RDE evaluation factors is to account for harsher than usual driving conditions during the RDE test. However, the RDE regulation already includes two other elements limiting aggressive driving: dynamic boundary conditions (see preceding section) and a trip validity check by comparing the RDE CO_2 to the vehicle's CO_2 characteristic curve.



Conventional and hybrid vehicles:

$$r_k = \frac{CO_2 \text{ over RDE (g/km)}}{CO_2 \text{ over WLTC (g/km)}}$$

Plug-in hybrid vehicles:

$$r_k = \frac{CO_2 \text{ over RDE (g/km)}}{CO_2 \text{ over WLTC (g/km)}} \times \frac{0.85}{\text{RDE distance ratio, engine on}}$$

Figure 13. Function for calculating the RDE evaluation factor.

Using the current knowledge of the gap between average real-word and type-approval CO_2 emissions,[96] we estimate that around 19% of non-plug-in hybrid vehicles measured on the road would have CO_2 levels that would result in an RDE evaluation factor of less than one (i.e., r_k would be above 1.3; see Figure 13).

For plug-in hybrids, the evaluation method applies a second correction that depends on the distance share of the RDE test driven with the internal combustion engine on, and a generic fixed factor, set at 85%, aimed at representing the distance share driven with the engine on over the WLTC test in charge sustaining mode (see Figure 13). This generic estimate, based on industry recommendations, has not been subject to an independent verification. For example, research by the University of Rome,[97] commissioned by Toyota, shows that the Prius can cover 62.5% of the distance with zero emissions—that is, 37.5% of the distance with the engine on—over a 37 km route with mixed driving. In practice, the RDE evaluation factor of such a vehicle would be around 0.5. That is, the reported RDE emissions used for compliance assessment would be half of the pollutants actually emitted during the RDE test.

Current regulation

The concept of an RDE evaluation factor was introduced in the fourth package of the RDE regulation. The thresholds shown in Figure 13 for the calculation of the RDE evaluation factor, which are applicable for type approvals granted after January 1, 2020, are considered final. The 85% generic factor used for the calculation of the RDE evaluation factor for plug-in hybrid vehicles can still be subject to review by the Commission and can be revised as a result of technical progress.

International comparison

The European methodology, including the RDE evaluation factor, is being transposed into a GTR in the context of UNECE's GRPE.

Recommendations

The current use of the RDE evaluation factors is not technology independent and can result in an artificial gap between the RDE emissions reported and those occurring in the real world. We offer the following recommendations:

» **Eliminate the RDE evaluation factor for adjusting emissions downward.** RDE trips driven within the boundary conditions, and with 50% of the windows within the tolerances defined by the CO_2 characteristic curve, should not require additional correction factors, such as the RDE evaluation factor. The amendment required to make the RDE evaluation factor applicable to plug-in hybrids is a good example of the unwanted regulatory complexity added by such correction factors. As the call for regulatory simplicity continues to grow, the RDE evaluation factor must be at the top of the list of elements to be removed.

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[96] Uwe Tietge et al., *From Laboratory to road: A 2018 update of official and 'real-world' fuel consumption and CO2 values for passenger cars in Europe* (ICCT: Washington, DC, 2019), https://www.theicct.org/publications/laboratory-road-2018-update.

[97] Toyota Europe, Toyota Prius excels in zero emissions commuting study, September 7, 2016, https://newsroom.toyota.eu/toyota-prius-excels-in-zero-emissions-commuting-study/.

HOW TO GUARANTEE IT? PROVISIONS TO ENSURE LOW REAL-WORLD EMISSIONS OVER THE USEFUL LIFE

DURABILITY PROVISIONS

What is the issue?

The deterioration of emission control systems can have a significant impact on the in-use emissions of on-road vehicles. As an example, Figure 14 shows the average CO emissions of gasoline passenger cars, measured by remote sensing technology in London between 2017 and 2018.[98] The observable increase in CO emissions with vehicle age is symptomatic of deteriorated exhaust aftertreatment systems.

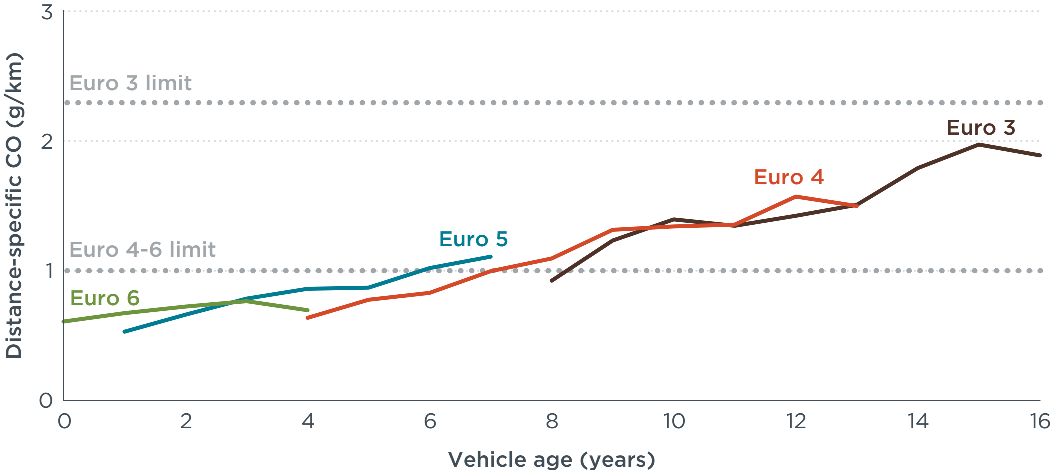

Figure 14. Average CO emissions as a function of vehicle age for gasoline vehicles measured with remote sensing technology. Adapted from Dallmann et al. (2018).

To guarantee the emissions performance of vehicles over their complete lifetime, in-service conformity (ISC) and minimum durability requirements are necessary. Current provisions limit the ISC to 5 years or 100,000 km, whichever occurs first, and outline the test procedures to determine the deterioration factors, which aim to verify the durability of emission control systems up to 160,000 km.

The average age of EU passenger cars was 11.1 years old in 2017[99] and varies significantly among Member States; in Luxemburg the average age is just 6.3 years, whereas in Lithuania cars are 16.9 years old on average.[100] The average age of the European fleet is increasing. For example, Germany—Europe's biggest car market—saw a 17% increase in

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[98] Tim Dallmann et al., *Remote sensing of motor vehicle emissions in London* (ICCT: Washington, DC, December 2018), https://www.theicct.org/publications/true-london-dec2018.

[99] ACEA, "Average vehicle age," January 6, 2019, https://www.acea.be/statistics/article/average-vehicle-age.

[100] ACEA, "Report: Vehicles in Use - Europe 2018," November 13, 2018, https://www.acea.be/statistics/article/report-vehicles-in-use-europe-2018.

average fleet age over the past 10 years.[101] A 2015 study[102] for the UK, which has Europe's second youngest fleet with an average age of 7.8 years,[103] found that diesel cars have an average retirement age of 14 years with an average lifetime mileage of over 200,000 km, whereas gasoline cars are retired at 14.4 years old and cover close to 160,000 km, and light commercial vehicles retire after 13.6 years with over 220,000 km.

The durability provisions only cover pollutant emissions and are not designed to guarantee CO_2, fuel consumption, or electric range performance throughout the useful life. The CO_2 deterioration of combustion engines is a consequence of the aging of the emission control system and the associated active engine measures required to compensate for this aging. Additionally, the CO_2 emissions of hybrid electric vehicles are sensitive to battery aging, as the engine needs to be operated more often and less braking energy can be recovered.

The durability, ISC, and warranty requirements set by current European regulations are too limited and are not representative of the average useful life of EU's LDV fleet.

Current regulation

The ISC provisions in the current Euro 6 standards establish that vehicles are eligible for ISC testing for a period of up to 5 years or 100,000 km, whichever comes first.

For demonstrating the durability of the pollution control system at type approval, manufacturers must conduct durability tests, which are designed to represent a vehicle that has traveled 160,000 km. To establish the deterioration factors whole-vehicle tests covering all vehicle systems, as well as bench aging tests covering only the aftertreatment system, are permitted for compression and positive ignition engines.[104] Alternatively, positive ignition engines can use generic deterioration factors instead of those determined by durability testing. There are no battery durability requirements nor ISC provisions for the electric range in charge depleting mode. The electric range directly influences the emissions through the utility factor used to report emissions.

An emissions warranty program does not currently exist in the EU. Manufacturers are not required to provide a warranty for vehicle emission controls, or to regularly report emissions-related warranty and repair claims, or any other emission defects.

The recently adopted LDV CO_2 standards[105] mandate the in-use verification of CO_2 emissions. However, a methodology does not yet exist.

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[101] Kraftfahrt-Bundesamt, "Fahrzeugalter - Bestand in den Jahren 2010 bis 2019 nach Ausgewählten Fahrzeugklassen mit dem Durchschnittsalter der Fahrzeuge," [Vehicle age - inventory in years 2010 to 2019 from selected vehicle classes with average age of vehicles] 2019, www.kba.de/DE/Statistik/Fahrzeuge/Bestand/Fahrzeugalter/fahrzeugalter_node.html.

[102] Craig Dun, Gareth Horton, and Sujith Kollamthodi, "Improvements to the definition of lifetime mileage of light duty vehicles" (Ricardo-AEA Ltd, December 3, 2015), https://ec.europa.eu/clima/sites/clima/files/transport/vehicles/docs/ldv_mileage_improvement_en.pdf.

[103] ACEA, "Report: Vehicles in use - Europe 2018."

[104] United Nations Economic Commission for Europe, "Regulation No. 83, Revision 5. Uniform Provisions Concerning the Approval of Vehicles with Regard to the Emission of Pollutants According to Engine Fuel Requirements," February 4, 2015, https://www.unece.org/fileadmin/DAM/trans/main/wp29/wp29regs/R083r5e.pdf.

[105] Parliament and Council of the European Union, "Regulation (EU) 2019/631 of the European Parliament and of the Council of 17 April 2019 Setting CO2 Emission Performance Standards for New Passenger Cars and for New Light Commercial Vehicles, and Repealing Regulations (EC) No 443/2009 and (EU) No 510/2011 (Text with EEA Relevance.)," *Official Journal of the European Union* L 111 (April 17, 2019), https://eur-lex.europa.eu/eli/reg/2019/631/oj.

International comparison

The United States and China have in-service conformity, durability, and emissions warranty requirements that are far more extensive than European requirements. Figure 15 summarizes the useful life requirements for ISC testing and durability demonstration in the European Union, the United States, and China.

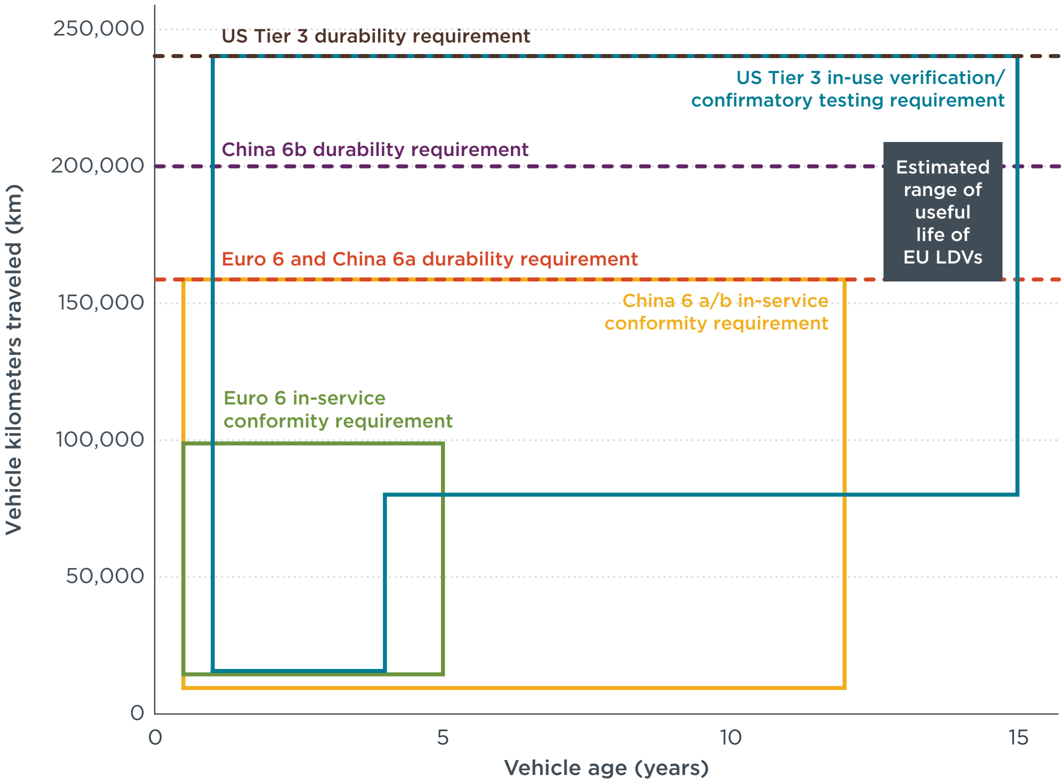

Figure 15. Useful life requirements for in-service conformity testing and durability demonstration in the EU, the United States, and China.

The U.S. in-use verification program requires low- and high-mileage testing. The high-mileage test vehicles must have a minimum odometer reading of 80,000 km and at least one vehicle of the test group must have a minimum odometer mileage of 169,000 km or 75% of the useful life, whichever is lower. The U.S. in-use confirmatory program establishes that test vehicles must be within the useful life, which for the U.S. Tier 3 standards can be up to 240,000 km (150,000 miles) or 15 years.

The durability requirements of the U.S. Tier 3 standards are aligned with the in-use verification and confirmatory programs; the durability of the emission control system must be demonstrated up to 240,000 km. Manufacturers can choose to certify vehicles to a useful life of 190,000 km, however those vehicles would have to meet emission limits that are 15% more stringent. Bench aging tests for durability demonstration are permitted only for gasoline engines. The durability of diesel-fueled vehicles must be demonstrated using the whole-vehicle durability procedure.

The China 6 a/b provisions for durability demonstration mimic those set by the Euro 6 standards; however, the duration of the tests is extended to represent 200,000 km to meet the China 6b standard, which will come into force in 2023. The useful life requirements for ISC test vehicles under the China 6 standards extend to 160,000 km or 12 years, whichever occurs first.

Emission warranty programs vary widely around the world.[106] U.S. legislation sets a minimum emission-related warranty period of 128,000 km (80,000 miles) or 8 years for key emission control components. Manufacturers can earn an emissions compliance credit for vehicles that are covered by an extended warranty period of 240,000 km (150,000 miles) or 15 years. China 6 introduced the first emission warranty and defect-reporting requirement in China, in which manufacturers are required to guarantee the integrity of emission-control parts for a minimum of 3 years or 60,000 km. Lastly, South Korea mandates a warranty period of 240,000 km or 15 years for gasoline LDVs and of 160,000 km or 10 years for diesel LDVs.

Emission defect reporting programs can provide information on the frequency of part failures in the emission control system and identify parts affecting emissions with abnormally high failure rates. Such programs exist in the United States, Japan, and South Korea. South Korea's program in particular is unambiguous and sets clear failure rate thresholds for reporting of a defect.

The United States is currently the only region that requires manufacturers to check and report CO_2 emissions from in-use vehicles. An in-use vehicle can be determined to be noncompliant if the CO_2 emissions exceed the certified value by more than 10%, although the U.S. Environmental Protection Agency has yet to report any of the in-use CO_2 emission test results.[107] For electrified road vehicles, China has a number of standards relating to the performance and durability of batteries.[108]

Recommendations

The current useful life provisions in the Euro standards for in-service conformity, durability, and emissions warranty requirements do not represent the average age and odometer readings of the European LDV fleet. We offer the following recommendations:

» **Extend the definition of useful life for durability demonstration.** The current definition of useful life is not representative of the EU fleet. The durability demonstration period should be extended, following the examples set by other major markets.

» **Establish whole-vehicle testing as the only option for durability demonstration.** Bench aging, which only captures the deterioration of aftertreatment systems, is no longer suitable for durability demonstration. The growing complexity of emission control systems, including combinations of engine adaptative calibrations, different engine components, catalytic converters, and particle filters, warrants a more comprehensive durability demonstration protocol. Future efforts should further

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[106] Zifei Yang and Rachel Muncrief, *Market Surveillance of Vehicle Emissions: Best-Practice Examples with Respect to the European Commission's Proposed Type-Approval Framework Regulation*, (ICCT: Washington, DC, July 2017), https://www.theicct.org/publications/market-surveillance-vehicle-emissions-best-practice-examples-respect-european.

[107] Zifei Yang, Rachel Muncrief, and Anup Bandivadekar, *Global Baseline Assessment of Compliance and Enforcement Programs for Vehicle Emissions and Energy Efficiency*, (ICCT: Washington, DC, November 2017), https://www.theicct.org/publications/compliance-and-enforcement-global-baseline.

[108] Vanesa Ruiz, *Standards for the Performance and Durability Assessment of Electric Vehicle Batteries* (Joint Research Centre of the European Commission, 2018), https://ec.europa.eu/jrc/en/publication/standards-performance-and-durability-assessment-electric-vehicle-batteries.

develop the whole-vehicle durability test, while eliminating the option of bench aging for the determination of the deterioration factors. Furthermore, if ISC tests show more deterioration than demonstrated at type approval, the manufacturer should be required to adjust the deterioration factor to reflect the ISC test results.

- **Extend the age and mileage requirements for vehicle selection for ISC testing and align those with the useful life provisions for durability demonstration.** The current age and mileage limits for ISC testing are significantly lower than the definition of the useful life under the durability demonstration provisions. ISC testing should be possible during the complete useful life of the vehicle.
- **Set a minimum emission warranty program.** An emission warranty program encourages vehicle owners to report and repair emission-related issues at no cost to the owner and incentivizes manufacturers to build durable emission control systems.
- **Set an emission defect tracking and reporting program.** An emission defect reporting program is a useful tool to collect information on the frequency of emission control part failures, identify emission parts with abnormally high failure rates, and take corrective actions. To ensure transparency and facilitate enforcement, clear thresholds for defect reporting must be set.
- **Develop a comprehensive ISC testing procedure for verifying CO_2 emissions, fuel/energy consumption, and electric range in charge depleting mode.** The LDV CO_2 standards mandate the Commission to develop an ISC test to verify CO_2 emissions of vehicles in service. The test should be developed to not only detect artificial improvements in the vehicle's CO_2 performance during type approval, but also to evaluate the deterioration of CO_2 emissions throughout the useful life of the vehicle. The scope of the ISC test also should include other energy related metrics such as the road load parameters, correction factors of regenerating systems (Ki), ambient temperature correction factors, electric energy consumption, and electric range in charge depleting mode.
- **Develop a battery durability test.** A battery durability test would enable estimating the decrease in electric range of electrified vehicles under real-world use. The test should be able to differentiate the aging attributed to either charge/discharge cycles or storage time. It is recommended that the outcome from any such durability testing be used to set deterioration factors affecting the declared vehicle range, energy efficiency, and CO_2 emissions.

ON-BOARD DIAGNOSTICS AND ON-BOARD MONITORING

What is the issue?

OBD systems are a fundamental element of emission control systems. OBD systems monitor the performance of emission control components during everyday driving and allow the identification of malfunctions that lead to higher pollutant emissions. To achieve this, the OBD system uses diagnostics software that takes the information of different vehicle sensors to infer the emissions performance and, if necessary, alert the driver to a possible issue through a malfunction indicator light (MIL).

The effectiveness of OBD systems in diagnosing the emission control system depends on which components and pollutants are monitored, the frequency of the monitoring, the definitions of what constitutes a malfunction, and on the actions taken once a fault is identified.

Compared to other major markets, the European OBD program is the least comprehensive.[109] It leaves the requirements to monitor several emission control systems open to interpretation instead of clearly defining them in the regulation. OBD systems, by design, do not detect malfunctions not explicitly listed in the OBD regulation.[110] Thus, the reduced scope of the European OBD program limits its effectiveness in identifying vehicle malfunctions that can lead to high emissions.

Current regulation

The current applicable OBD regulation in the EU, denoted as Euro 6-2, entered into force in September 2018 for all new vehicles. The regulation established new OBD threshold limits (OTLs) for the identification of component malfunctions and increased the monitoring frequency, or so called in-use performance ratio (IUPR), for the NO_x aftertreatment system of diesel engines.

In the current European OBD program, the monitoring conditions for most emission related systems are left exclusively to the manufacturer, as can be inferred from the vague regulatory language and the fact that the requirements for many important systems are grouped under broad category of "other emission control systems."

The latest changes to the European type-approval regulation stipulate that, from January 2020 onward, new vehicle types must be equipped with onboard fuel consumption meters to determine the instantaneous as well as the lifetime fuel consumption of each vehicle. However, the regulation does not extend the onboard monitoring requirement to emissions of pollutants.

International comparison

California's OBD II program is the most comprehensive program in the world and is the basis of the Chinese, European, and Korean programs. This program sets the bar for general OBD requirements, MIL illumination, and diagnostic trouble code (DTC) storage. The program established specific OTLs and unambiguous criteria for malfunctions, monitoring conditions, MIL activation, and DTC storage and erasing. The differences between the programs in California and Europe are vast and complex. In summary, the California OBD II program monitors significantly more systems and situations than those covered by the European OBD provisions, requires the permanent storage of DTCs, and requires a much more robust demonstration testing of the OBD functionalities. Further information can be found in an ICCT report comparing the OBD programs in California and Europe.[111]

Although the China 5 OBD program largely followed the European program, the China 6 OBD provisions are now largely based on the California OBD II program, excluding a few monitoring requirements.[112] Going beyond the European provisions, the China 6 OBD program includes monitoring of leaks from evaporative emission control systems,

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[109] Francisco Posada and John German, *Review of LDV OBD requirements under the European, Korean and Californian emissions programs* (ICCT: Washington, DC, March 31, 2016), https://www.theicct.org/publications/review-ldv-obd-requirements-under-european-korean-and-californian-emission-programs.

[110] Janean Potter, "On-board diagnostics (OBD) worldwide requirements" (SAE 2019 European On-Board Diagnostics Symposium, Stuttgart, Germany, 2019).

[111] Posada and German, *Review of LDV OBD Requirements under the European, Korean and Californian Emissions Programs.*

[112] Hui He and Liuhanzi Yang, China's Stage 6 Emission Standard for New Light-Duty Vehicles (Final Rule), (ICCT: Washington, DC, March 16, 2017), https://www.theicct.org/publications/chinas-stage-6-emission-standard-new-light-duty-vehicles-final-rule.

as well as anti-tampering and anti-fraud requirements, such as permanent DTC storage, calibration identification numbers, and calibration verification numbers.

California[113] and China[114] have adopted on-board emissions monitoring (OBM) regulations requiring heavy-duty vehicle (HDV) OBD systems to collect and store emissions data from the vehicle's sensors. These data can be used by the regulatory agencies for improving in-use compliance and improving the effectiveness of inspection and maintenance programs. The regulatory framework has not been extended to LDVs in either region.

Recommendations

A robust and unambiguous OBD and OBM regulation is instrumental in improving the durability and performance of emission control systems. This, in turn, contributes to translating the reductions mandated by the standards into lower in-use emissions. The current OBD program in Europe leaves the requirements for monitoring several emission control systems open to interpretation and can fail to identify malfunctions that can lead to high emissions. We offer the following recommendations:

- **Align the OBD requirements with those of California and China.** California's OBD II program, the most comprehensive program in the world, includes the largest set of monitored components and systems, as well as stringent guidelines for MIL illumination and fault code storage. In the latest iteration of its emission standards, China adopted OBD provisions largely based on the Californian program and moved away from the European one.
- **Introduce on-board monitoring of pollutant emissions.** Requiring vehicles to collect and store the pollutant emission measurements and estimates from the vehicle's own sensors and models enables regulators to identify durability issues faster, helps ensure that vehicles maintain low emissions throughout their full lives, and permits demand-based periodic technical inspections. On-board fuel consumption meters are now part of the type-approval requirements. This regulatory framework can be expanded to also monitor pollutant emissions and positions Europe to be the first market to introduce an OBM emission program for light-duty vehicles.
- **Set an OTL for particle number and reduce the OTLs for other pollutants.** The criteria for identifying malfunctions are implemented in the regulation as emission thresholds. Regulation (EU) 459/2012 introduced the possibility of an OTL for PN emissions, stating that "setting a particle number Euro 6 OBD threshold limit should be evaluated at a later stage." However, a PN OTL has not yet been proposed and should be addressed in the upcoming regulation. European OTLs for other pollutants are higher than those adopted in other regions and should be revised downward.
- **Strengthen the anti-tampering provisions.** To prevent the use of SCR emulators, also called AdBlue killers, the removal of aftertreatment components, the obstruction of exhaust gas recirculation (EGR) valves, or the reprogramming of the

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[113] California Air Resources Board, "CARB gets 'REAL' to further cut pollution from diesel and gas vehicles | California Air Resources Board," November 15, 2018, https://ww2.arb.ca.gov/news/carb-gets-real-further-cut-pollution-diesel-and-gas-vehicles.

[114] MEE, "Limits and measurement methods for emissions from diesel fueled heavy-duty vehicles (CHINA VI)" (People's Republic of China, June 22, 2018), http://kjs.mee.gov.cn/hjbhbz/bzwb/dqhjbh/dqydywrwpfbz/201807/t20180703_445995.shtml.

engine control unit, the regulation must mandate and support the development of tamperproof systems. The scope and design of the OBD program should be extended to include a stronger focus on inhibiting tampering attempts.

MARKET SURVEILLANCE AND ENFORCEMENT

What is the issue?

Whereas some deviations between certified and real-world emissions of vehicles are unavoidable, excessive in-use emissions and a persistent disparity between certified and real-world emissions erodes public trust in vehicle manufacturers and the institutions regulating them. Thus, market surveillance and robust compliance and enforcement (C&E) programs are indispensable elements of emission regulations.

Market surveillance refers to the independent verification, testing, and inspection of vehicles by regulatory agencies. Robust enforcement provisions include punitive elements such as type-approval revocations, recalls, fiscal penalties, consumer compensation, and legal prosecution.

While the new EU type-approval framework, adopted in 2018 and to be implemented in 2020, constitutes a major revision, it largely maintains the basic architecture of the European type-approval system and further elements need to be strengthened.

Current regulation

In 2018 an overhaul of the EU type-approval framework, applicable from September 2020 onward, was adopted.[115] In the new framework the European Commission has the authority to carry out its own verification testing, to initiate and monitor vehicle recalls, and to impose fines on manufacturers. The European Commission is also allowed to perform market surveillance tests on vehicles already on the road in order to detect and correct poor real-world emissions performance caused by illegal defeat devices or durability issues, among others. The European Commission can also impose fines of up to 30,000 euros per noncompliant vehicle on manufacturers in cases where a penalty has not been previously issued by a Member State.

EU Member States are also empowered to take measures against noncompliant vehicles sold in their national markets. Regardless of where the vehicles were type-approved, Member States can restrict or prohibit the use of affected vehicles and can require corrective actions of manufacturers. Member States are required to establish market surveillance authorities independent of the type-approval authority, which must conduct a minimum number of vehicle compliance tests per year. At least one compliance test must be conducted per every 40,000 new motor vehicles registered in the respective Member State in the preceding year, with at least 20% of the tests emissions-related.

In the new framework, the financial relationship between manufacturers and technical services continues to exist. Technical services, which perform certification testing and inspection, are in turn paid directly by manufacturers. This leads to conflicts of interest and casts a shadow on the impartiality of the certification activities.

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[115] Parliament and Council of the European Union, “Regulation (EU) 2018/858 of the European Parliament and of the Council of 30 May 2018 on the Approval and Market Surveillance of Motor Vehicles and Their Trailers, and of Systems, Components and Separate Technical Units Intended for Such Vehicles, Amending Regulations (EC) No 715/2007 and (EC) No 595/2009 and Repealing Directive 2007/46/EC (Text with EEA Relevance.),” *Official Journal of the European Union* L 151 (June 14, 2018), http://data.europa.eu/eli/reg/2018/858/oj.

International comparison

The U.S. C&E program is the oldest and most comprehensive in the world, with a strong focus on in-use testing and a solid record of recalls and other corrective enforcement actions. The program has a strong technical expertise and fosters an environment where the cost of noncompliance is an effective deterrent. Canada's C&E program acts as a complement to the U.S. program by focusing its testing efforts on vehicles that are not sold in the United States.

Japan and South Korea have structured C&E programs with strong legislative support, clear governmental liability, well defined penalties, and adequate corrective methods for noncompliance. Both countries monitor compliance with independent testing. China and India do not have well established C&E programs, on the other hand. In China, however, the latest vehicle emission standards include strengthened compliance and testing requirements, and the enforcement framework has been reinforced. While waiting for the enhanced emission regulatory system to take effect, boosting C&E of fuel efficiency standards becomes more imperative in China.

Further details on the C&E programs around the world can be found in a separate ICCT white paper.[116]

Recommendations

The new type-approval framework is a significant first step in introducing a robust market surveillance and C&E program in the European Union. However, the regulatory text is not comprehensive enough and leaves details open to interpretation. We offer the following recommendations:

- **Develop a standardized methodology for fleet screening to identify potentially noncompliant vehicle models.** Under the current framework, neither the European Commission nor the Member States have established systematic information sources to identify potential high emitting in-use vehicles. Emissions warranty and defect reports, inspection and maintenance data, on-board diagnostic system records, and remote sensing are viable screening methods. Member States should leverage multiple data sources to monitor as large a sample of the in-use fleet as possible. These databases should be shared with the European Commission and other Member States.
- **Develop a remote sensing standard and establish a Europe-wide database of remote sensing records.** Remote sensing is a very effective technology for identifying high emitters, enabling robust and targeted market surveillance, particularly if the remote sensing records are consolidated and shared across market surveillance authorities. The development of a remote sensing standard enables its consistent application across Member States.
- **Clarify the criteria for failure of market surveillance tests.** The framework does not specify how to determine when a vehicle fails the market surveillance test. The implementation of streamlined guidance for market surveillance authorities to

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[116] Yang, Muncrief, and Bandivadekar, *Global Baseline Assessment of Compliance and Enforcement Programs for Vehicle Emissions and Energy Efficiency.*

determine noncompliance through in-depth testing[117] is essential to build up the necessary evidence base for enforcement.

- **Issue guidance on defeat devices.** Conclusively determining whether or not a vehicle has a defeat device to circumvent emissions tests is difficult. Adopting clear criteria to approve or reject exception claims to the defeat device prohibition would be an important step to reduce the legal ambiguity used by manufacturers to justify defeat devices. For example, a common exception claim is the protection of engine components. The regulation should clearly state that auxiliary emission strategies for component protection stemming from inadequate design or technology selection are not justified.[118]
- **Extend the scope of market surveillance beyond pollutant emissions.** The market surveillance activities should be extended to include parameters declared by the manufacturers in the type-approval process that can have a direct impact on vehicle emissions. These include verification of road-load parameters, charge depleting electric range, correction factors of regenerating systems (Ki), and ambient temperature correction factors, among others.

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[117] Yoann Bernard et al., Catching Defeat Devices: How Systematic Vehicle Testing Can Determine the Presence of Suspicious Emissions Control Strategies (ICCT: Washington, DC, June 20, 2019), https://theicct.org/publications/detecting-defeat-devices-201906.

[118] Tim Grabiel and Pete Grabiel, “Strengthening the regulation of defeat devices in the European Union” (Défense Terre, August 12, 2016), https://theicct.org/publications/strengthening-regulation-defeat-devices-european-union.

FINAL REMARKS

The ICCT commends the commitment of the European Commission to continue to address on-road emissions through a new phase of pollutant emission standards. With this report, the ICCT seeks to bring attention to a long list of important issues. The breadth and depth of topics that must be addressed in the coming months will require uninterrupted efforts of the Commission, its contractors, and all other stakeholders invested in reducing the environmental impact of road transport.

The ICCT will continue to actively contribute in the upcoming process, leading to the release of a strong regulatory proposal by the Commission by the end of 2020 or early 2021. The ICCT expects the post-Euro 6 emission standards to begin implementation in 2025, more than a decade after the first implementation steps of the current Euro 6 standards.

ABBREVIATIONS

AES	Auxiliary emission strategies
AQGs	Air quality guidelines
C&E	Compliance and enforcement
CF	Conformity factor
CH_4	Methane
CI	Compression ignition
CO_2	Carbon dioxide
CO	Carbon monoxide
DPF	Diesel particulate filter
DTC	Diagnostic trouble code
EGR	Exhaust gas recirculation
FID	Flame ionization detector
FTP	Federal Test Procedure
GDI	Gasoline direct injection
GHG	Greenhouse gas
GPF	Gasoline particulate filter
GRPE	Working Party on Pollution and Energy
GTR	Global technical regulation
GWP	Global warming potential
HC	Hydrocarbons
HDV	Heavy-duty vehicle
ISC	In-service conformity
IUPR	In-use performance ratio
LCV	Light commercial vehicle
LDV	Light-duty vehicle
LNT	Lean NOx trap
MIL	Malfunction indicator light
N_2O	Nitrous oxide
NEDC	New European Driving Cycle
NMHC	Non-methane hydrocarbons
NMOG	Non-methane organic gases
NO_2	Nitrogen dioxide
NO_x	Nitrogen oxides
O_3	Ozone
OBD	On-board diagnostics
OBM	On-board monitoring
ORVR	On-board refueling vapor recovery system
OTL	OBD threshold limit
PEMS	Portable emissions measurement system

PFI	Port fuel injection
PI	Positive ignition
PM	Particulate matter
PM_{10}	Particulate matter larger than 10 microns
$PM_{2.5}$	Particulate matter larger than 2.5 microns
PMP	Particle Measurement Programme
PN	Particulate number
RDE	Real Driving Emissions
RPA	Relative positive acceleration
SC03	U.S. supplemental federal test procedure
SCR	Selective catalytic reduction
THC	Total hydrocarbon
TWC	Three-way catalyst
UNECE	United Nations Economic Commission for Europe
US06	U.S. supplemental federal test procedure
VOC	Volatile organic compounds
WHO	World Health Organization
WLTC	Worldwide harmonized Light Duty Test Cycle
WLTP	Worldwide Harmonized Light Vehicle Test Procedure

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