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On-road vehicle emissions beyond RDE conditions

Experimental assessment addressing EU Real-Driving Emission (RDE)

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Contents

Foreword

Directorate C Sustainable Transport Unit (unit C4) designed and carried out a testing campaign during 2017 and 2018 using **tests outside Real-driving emissions (RDE) boundary conditions and experimental work** in the context of the **Administrative Arrangement ENV-070201-JRC.743134 entitled Real Driving emissions of new diesel vehicles.**

This technical report is an assessment on real world performance and emission factors of some of the top selling diesel and gasoline cars models of the EU market. The document includes an evidence based assessment for policy making addressed to DG ENV. The report describes the evaluation on real world performance and the production of emission factors of representative top selling diesel and gasoline cars models of the EU market. This report also includes the data of the most relevant results regarding the behaviour of those cars when running beyond the so called "extended conditions", meaning cold ambient temperature (<-7°C), high altitude (>1300m), as well as high vehicle driving dynamics. All data collected will be published as peer reviewed articles[1].

The experimental campaign was planned with a proactive and forward-looking frame. The STU has developed its capacity to anticipate future policy actions in relevant areas of vehicle pollutant emissions. Therefore, the output of the AA contains data on various powertrain (diesel, gasoline, natural gas and plug-in hybrid). It presents and discusses **on road emissions of NOx, NO_2, CO, PN and CO_2 from twenty-one Euro 6b, or newer vehicles**, including ten **diesel** (three of which are certified to Euro 6d-TEMP), nine **gasoline** (direct injection (GDI) and port fuel injection (PFI), one of which is certified to Euro 6d-TEMP), one **plug-in hybrid** and one **CNG** vehicles.

Although RDE accounts for a large share of real-world driving, it excludes certain driving situations by setting boundary conditions (e.g., in relation to altitude, temperature or dynamic driving). The vehicles were investigated in different on-road scenarios and exploring the emissions taking place **when vehicles were tested outside the RDE boundary conditions and compared to tests performed using RDE routes.**

[1] Suarez-Bertoa Ricardo, Valverde Victor, Clairotte Michael, Pavlovic Jelica, Giechaskiel Barouch, Franco Vicente, Kregar Zlatko, and Astorga Covadonga. On-road emissions of passenger cars beyond the boundary conditions of the Real-Driving Emissions test. Environmental Research. 176, 108572, 2019.

Suarez-Bertoa Ricardo, Valverde Victor, Pavlovic Jelica, Clairotte Michael, Franco Vicente, Kregar Zlatko, and Astorga Covadonga. On-road emissions of Euro 6 gasoline, diesel and plug-in hybrid passenger cars on Alpine routes during winter period. Atmospheric Environment. *Submitted*. 2019

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Abstract

Passenger cars are an important source of air pollution, especially in urban areas. Recently, real-driving emissions (RDE) test procedures have been introduced in the EU aiming to evaluate nitrogen oxides (NOx) and particulate number (PN) emissions from passenger cars during on-road operation. Although RDE accounts for a large share of real-world driving, it excludes certain driving situations by setting boundary conditions (e.g., in relation to altitude, temperature or dynamic driving).

The present work investigates the on-road emissions of NOx, NO_2, CO, particle number (PN) and CO_2 from a fleet of twenty-one Euro 6b, 6c and 6d-TEMP vehicles, including diesel, gasoline (GDI and PFI) and compressed natural gas (CNG) vehicles. The vehicles were tested under different on-road driving conditions both inside and outside of RDE boundaries. These included 'baseline' tests within RDE conditions, but also testing in conditions beyond the RDE boundary conditions to investigate the performance of the emissions control devices in demanding situations.

Consistently, low average emission rates of PN and CO were measured from all diesel vehicles tested under most conditions. Moreover, the tested Euro 6d-TEMP and Euro 6c diesel vehicles met the NOx emission limits applicable to Euro 6d-TEMP diesel vehicles during RDE tests (168 mg/km). Some of the vehicle met this limits even outside the RDE boundaries. The Euro 6b GDI vehicle equipped with a gasoline particulate filter (GPF) presented PN emissions $< 6\times10^{11}$ #/km. These results, in contrast with previous on-road measurements from earlier Euro 6 vehicles, indicate more efficient emission control technologies are currently being used in diesel and gasoline vehicles.

However, the results described in this report also raise some new concerns. In particular, the emissions of CO (measured during the regulated RDE test, but without an emission limit associated to it) or PN from PFI vehicles (presently not covered by the Euro 6 standard) showed elevated results in some occasions. Emissions of CO were up to 7.5 times higher when the more dynamic tests were conducted and the highest PN emissions were measured from a PFI gasoline vehicle during dynamic driving.

The work also investigates how NOx, CO, PN and CO_2 on-road emissions from three vehicles are impacted by sub-zero ambient temperatures and high altitudes. Two of the tested vehicles were Euro 6d-TEMP certified vehicles, one diesel and one gasoline, and one was a Euro 6b plug-in hybrid vehicle. The vehicles were studied during tests that do not fulfil the boundary conditions in terms of maximum altitude, altitude gain, and/or minimum temperature. The obtained emissions were compared to those obtained during tests performed along RDE routes.

The results indicate that cold ambient temperature and high altitude, outside the RDE boundary conditions, lead to in higher NOx, CO and PN emissions compared to moderate conditions of temperature and altitude. **Nonetheless, the two Euro 6d-TEMP vehicles tested in those extreme conditions yielded NOx emissions factors that fulfilled the Euro 6d-TEMP emission requirements**.

Our work underlines the importance of a technology- and fuel-neutral approach to vehicle emission standards, whereby all vehicles must comply with the same emission limits for all pollutants.

1 Introduction

Air pollution remains the most important environmental cause of premature death in the EU as well as globally. Despite notable improvements during the last decades, poor air quality continues to cause over 400 000 premature deaths in the EU each year. Moreover, air quality present other health and environmental impacts which extend to acute and chronic respiratory, cardiovascular and other diseases and associated socio-economic costs. The European Clean Air Programme considers the high concentrations of particulate matter, nitrogen dioxide and ground-level ozone of most concern. Hence the strategic objectives are set accordingly based on an extensive evaluation and impact assessment [SWD, 2013]. It is furthermore noted that, for some air pollutants, EU air quality standards are less strict than the specific guideline values provided by World Health Organization [WHO, 2005]. To achieve compliance with the EU air quality standards and, in the long term, move towards those stated in the WHO guidelines, air pollutant emissions need to be reduced at local, national and transboundary levels.

Recent seasonal studies have shown that in some urban areas the highest levels of NOx, NH_3, CO and PM occur in the cold season [Hofman et al., 2016; Hama et al., 2017]. Those studies, as well as the recent report presented by the European Environment Agency [EEA, 2018], indicate that transport sector is among the main sources of NOx, CO, volatile organic compounds (VOCs), primary aerosols and secondary aerosol precursors [EEA, 2018; Gordon et al., 2014; Platt et al., 2017; Suarez-Bertoa et al., 2015; Link et al.,2017; Anenberg et al, 2017]. These pollutants play key roles in the formation of tropospheric ozone (O_3) and secondary aerosols that impair air quality. Winter season, in particular, is associated with high pollution episodes [Custódio et al. 2016; Wang et al. 2017].

The successive revisions of the EU type approval legislation aimed at reducing emissions from cars through the introduction of the respective EURO standards (1 to 6). The latest focus was on PM and NOx. Already in 2011 it was acknowledged that cars could emit more than the legal standards under real-driving conditions, thereby confirming earlier speculations about a growing problem in this field. The difference in emissions could be anywhere between 2 to 20 times the legal emission limits for Euro 5 diesel vehicles. The Volkswagen case has brought this matter to the forefront of the political agenda both in the EU and in the Member States, and has undermined consumer confidence in the car industry and the regulators.

Although RDE accounts for a large share of real world situations there are several **boundary conditions** that were introduced to allow the test to be representative of European real driving. These boundary conditions include: **vehicle dynamics, positive altitude gain, speed share of operations, ambient temperature**, among others. Moreover, the RDE requires not-to-exceed limits (NTE) only for NOx and solid particle number (PN) emissions. As for laboratory type-approval procedure, in RDE the PN limit only applies for diesel (DV) and gasoline direct injection vehicles (GDI), while in the laboratory type-approval procedure there is a limit for CO. Therefore, a series of situations, such as on-road CO emissions, PN emissions from port fuel injection (PFI) gasoline vehicles, off-boundary condition testing, are not covered by the current RDE regulation.

1.1 Scope of the study

The overall objective of this work is to gain targeted independent evidence and assessments about the sector's progress in reducing real-driving exhaust emission levels of air pollutants from new vehicles reaching the EU market.

Efforts of the experimental work focused on testing and assessing some of the most popular new models on the European market, as these are assumed to account for the largest fraction of the total emissions, especially in urban areas. This approach provides further technical input to vehicle emissions policy concerns by the European Commission, particularly in relation to considerations towards setting up a voluntary system for identification of low emission vehicles.

Another objective was to provide a better indication of the current state of real-driving emissions to the Commission and the public at large. The JRC has already been performing real world testing of light duty vehicles for many years now, as documented in several publications [Weiss et al., 2011; 2012; 2013; Giechaskiel et al., 2014]. JRC has also been fully involved in the preparation of the RDE [2016/646; 2017/1151; 2018/1832] acts, supporting discussions with scientific evidence throughout the whole process and has been actively involved in setting new emission factors for use in air quality modelling through the ERMES group. The specific objectives of this study were as follows:

Box 1. Objectives of the experimental program.

Objective 1 - Assess real world performance of some of the best-selling models on the EU market.

This part focussed on the newest and most popular diesel and gasoline models sold, ranked by their most recent total sales in the EU. Recently type-approved vehicles (presumably engineered with RDE provisions in mind) were prioritized. It is necessary to test the most recent vehicles sold, because in a normal vehicle life cycle, it is expected that these will be on the market for longer. Also, a few independent studies [Franco et al., 2014, Kadijk et al., 2016] that have investigated vehicle exhaust emissions have focused on the higher and more expensive end of the market. Therefore, a better coverage of lower vehicle market segments was desirable.

Objective 2 - Contribute to production of appropriate emission factors for these vehicles

Policy makers and stakeholders that deal with exceedances of air pollutants concentrations need to know the emission performance of most popular vehicles with sufficient detail. Up-to-date emission factors must be used in emission and air quality modelling in order to evaluate the effectiveness of newer diesel technology (driven by the phase-in of mandatory RDE not-to-exceed limits). The data resulting from the vehicle testing be made available to the broad community of emission modelers, specifically to the ERMES network.

Following the aforementioned objectives, the present work investigates the emissions of NOx, NO_2, CO, PN and CO_2 from a fleet of 21 Euro 6b+ vehicles, including diesel, gasoline (GDI and PFI) and CNG vehicles, under different driving conditions. Emissions of the vehicles tested during RDE compliant tests, which act as base line, were compared to emissions obtained during tests that do not fulfil the boundary conditions in terms of dynamicity (excessively dynamic driving), share of operation (too long urban and/or motorway shares), altitude gain (excessive altitude gain), among others. Table 1 summarizes a not exhaustive list of these requirements and boundary conditions for a test to be RDE compliant.

The work does not only shed light on the current state of vehicle emissions under different real world conditions but it is an important source for emission factors. The obtained emission factors will allow updating current vehicle emissions inventories providing real world emissions of pollutants that are not included in on-road regulation at the moment (CO and PN from PFI). Moreover, it presents some of the first results of vehicles type-approved under the most stringent emission standards at the moment (Euro 6d-TEMP) investigated under different real-world driving situations.

The RDE procedure requires the measurement of NOx and PN for all passenger cars (with the exception of PN from non-direct injection gasoline vehicles, i.e., port fuel injection – PFI) at ambient temperature as low as -2°C for vehicles type-approved as Euro 6d-TEMP vehicles and down to -7°C for those type approved after 1 September 2019. The current laboratory-based test at cold temperature (-7 ±3°C) only requires the measurement of total hydrocarbon (THC) and CO emissions from gasoline vehicles (see Figure 1), with a limit for the emissions which are more than 15 times higher than those allowed during Type 1 test performed at 23 ±5 °C.

Figure 1. Cold ambient laboratory test for light-duty vehicles. Global state of play.

	T °C	Cycle	Road-Load	Vehicles	Pollutants
	−7.0 ±3	UDC	Determined at -7°C or 10% reduction of coast-down time	P.I. including hybrids + information regarding NOx after-treatment for C.I.	HC, CO
	−7.0 ±3	UDC	"	"	THC, CO
	−7.0 ±1.7	FTP	Performing coast-down tests and calculating road-load coefficients	Otto-cycle and diesel including multi-fueled, alternative fueled, hybrid electric, and zero emission vehicles	NMHC, CO, CO_2 *
	−6.7	CVS-75	"	Gasoline + information regarding NOx after-treatment for C.I.	CO
	−7.0 ±3	Low+ Medium of WLTC	Determined at -7 C or 10% reduction of coast-down time	P.I. C.I. hybrids	THC, CO, NOx

* CO_2 is analysed and results used for the determination of the vehicle fuel economy. Cold temperature standards apply for CO and NMHC emissions.

Therefore, it is also in the scope of this study to investigate how sub-zero ambient temperatures and high altitudes impact the on-road emissions of NOx, CO, PN and CO_2 from two Euro 6d-TEMP certified vehicles, one diesel (DV8) one gasoline (GV9), and one Euro 6b plug-in hybrid vehicle (PHEV).

The vehicles were studied during tests that do not fulfil the boundary conditions in terms of maximum altitude (one route reaches >2000 m.a.s.l.), altitude gain (altitude gain >1200m/100km), and/or minimum temperature (< -2°C) and the emissions were compared to those obtained during tests performed fulling most of the requiring RDE regulation. These tests acted as base line. Emissions during the urban section of the on-road tests as well as during cold start were also evaluated as they could have a higher impact on urban air quality.

Box 2. Supporting material and information.

The present report was based on the data of the most relevant results concerning the behaviour of the studied cars when running beyond the so called "extended conditions", meaning cold ambient temperature (<-2°C), high altitude (>1300m), as well as high vehicle driving dynamics, presented in the following peer reviewed articles:

Suarez-Bertoa Ricardo, Valverde Victor, Clairotte Michael, Pavlovic Jelica, Giechaskiel Barouch, Franco Vicente, Kregar Zlatko, and Astorga Covadonga. On-road emissions of passenger cars beyond the boundary conditions of the Real-Driving Emissions test. Environmental Research. *Submitted.*2019.

Suarez-Bertoa Ricardo, Valverde Victor, Pavlovic Jelica, Clairotte Michael, Franco Vicente, Kregar Zlatko, and Astorga Covadonga. On-road emissions of Euro 6 gasoline, diesel and plug-in hybrid passenger cars on Alpine routes during winter season. Atmospheric Environment. *Submitted*. 2019.

Table 1. Some of the requirements and boundary conditions for a test to be RDE compliant.

Altitude (m.a.s.l.)	Moderate conditions	0 – 700
	Extended conditions	700 – 1300
Ambient temperature	Moderate conditions	0 – 30 °C
	Extended conditions	−7 – 0 °C and 30 – 35 °C
Cumulative positive elevation gain		1200 m every 100 km
Altitude difference between start and finish		<100 m
Dynamics	Upper limits	95th percentile of the multiplication of the instant speed and positive acceleration signals as defined in Appendix 7a, Section 4 of RDE 3.
	Lower limits	Relates to the relative positive acceleration as defined in Appendix 7a, Section 4 of RDE 3.
Maximum speed		145 km/h (up to 160 km/h for <3% of motorway driving time).
Payload		Maximum 90% of the maximum vehicle weight (including the mass of the driver and measurement equipment).
Stop percentage		Between 6% and 30% of the urban driving time.
Speed	Average urban speed	15 – 40 km/h
		above 100 km/h for at least 5 minutes.
Distance		Urban >16 km; Rural >16 km; Motorway >16 km
Trip Composition		Urban 29 – 44% of the total distance; Rural 23 – 43% of the total distance; Motorway 23 – 43% of the total distance.
Total Trip Duration		90 – 120 minutes
Use of auxiliary systems		Operated as in real life use (air conditioning, etc.).

2 Research methodology: Results and discussion

Two experimental campaigns were conducted by the Sustainable Transport Unit of the European Commission Joint Research Centre (EC-JRC) between March 2017 and December 2018 aiming at investigating the impact that driving style, shares of operation, cold ambient temperature and high altitude could have on vehicle emissions during real life driving.

In order to investigate the impact of driving style and/or shares of operation, emissions of NOx, NO_2, CO, PN and CO_2 from 19 Euro 6 vehicles (see Table 3 and Table 4 for main characteristics and for further details including brand and model) were comprehensively studied under different driving conditions.

The fleet comprised, 8 gasolines (7 Euro 6b and 1 Euro 6c), 10 diesels (6 Euro 6b, 1 Euro 6c and 3 Euro 6d-TEMP) and 1 Euro 6b CNG light commercial vehicle (hereinafter CNG-LCV). The vehicles were tested during RDE-compliant tests, which act as baseline, and also during tests that do not fulfil RDE boundary conditions in terms of dynamicity (excessive dynamic driving), share of operation (urban and/or motorway shares above RDE requirements), altitude gain (excessive altitude gain), among others. The vehicles were tested with PEMS over four different pre-defined routes in the Italian region of Lombardy: two fully RDE-compliant (route identifiers RDE-1 and RDE-2) and 2 non-RDE compliant (City-Motorway and Hill) (see Table 2).

To investigate the impact of cold ambient temperature and high altitude, on the NOx, CO, PN and CO_2 emissions from one Euro 6d-TEMP gasoline (GV9), one Euro 6d-TEMP diesel (DV8) and one Euro 6b gasoline-PHEV were comprehensively studied. The vehicles were tested during: i) Two RDE-compliant routes (route identifiers RDE-1 and RDE-2; hereinafter RDE-routes), which act as baseline, ii) one on-road test that does not fulfill RDE boundary conditions in terms of minimum temperature (< -2°C) and is at the high end of the maximum altitude boundary (Max. altitude 1300 m.a.s.l.) (hereinafter Alpine-1) and iii) one on-road test that do not fulfill RDE boundary conditions in terms of maximum altitude (one route reaches >2000 m.a.s.l.), altitude gain (altitude gain >1200m/100km), and minimum temperature (< -2°C) (hereinafter Alpine-2). Table 2 summarizes the main features of the tests performed.

The vehicles used in this study were selected to be a representative sample of the European market for new vehicles. The tested fleet included some of the best-selling models from different manufacturers across vehicle segments and engine sizes. The vehicles were equipped with the usual exhaust after-treatment technologies in the EU for new cars sold between 2016 and 2018. Gasoline vehicles used either port fuel injection (PFI) or direct injection (GDI) technology. One gasoline vehicle (GV8) was equipped with a gasoline particulate filter (GPF). All diesel vehicles were equipped with an exhaust gas recirculation (EGR) system and either a lean NOx trap (LNT), selective catalytic reduction (SCR) or both (DV9) to control NOx emissions. One diesel vehicle (DV10, type-approved to Euro 6d-TEMP) was equipped with a dual LNT and a passive SCR (not requiring urea solution refills).

Table 2. Trips characteristics. Bold indicates that the value is outside RDE boundary conditions.

	RDE compliant routes		Non-RDE compliant routes					
	RDE-A	RDE-B	RDE-A-Dyn.	RDE-B-Dyn.	City-MW	Hill	Alpine-1	Alpine-2
Trip distance (km)	79	94	79	94	139	61	87	84
Av. trip duration (min)	98	112	94	104	**136**	106	108	91
Ambient Temperature (ºC)	11–27	7–32	5–30	9–33	**8**–30	**5–31**	-5	-6 – -7
Av. Urban distance (km)	32	37	31	34	44	61	36	36
Av. Rural distance (km)	25	27	25	28	18	-	24	22
Av. MW distance (km)	22	30	23	32	80	-	27	25
Urban av. Speed (km/h)	29	29	29	31	31	34	29	37
Av.Urban 95th *v*a* (m^2/s^3)	13	13	**20**	**20**	10	9	8	11
Av. Rural 95th *v*a* (m^2/s^3)	19	17	**29**	**30**	19	-	16	19
Av. MW 95th *v*a* (m^2/s^3)	19	21	**29**	**30**	18	-	21	17
Cumulative positive gain (m/100km)	760	820	760	820	440	**1830**	1015	**1687**
Max trip altitude (m)	300	415	300	415	295	1088	**1380**	**2040**

Table 3. Vehicle specifications. Gasoline vehicles (GV), plug-in hybrid vehicle (PHEV) and compressed natural gas light commercial vehicle (CNG-LCV).

Code	Brand	Model	Fuel	Inj.	Emission Control system	Reg. Year	Euro standard	Engine Capty. (cm^3)	Power (kW)
GV1	Fiat	Panda	Gasoline	PFI	TWC	2016	Euro 6b	1242	51
GV2	Renault	Twingo	Gasoline	PFI	TWC	2017	Euro 6b	999	51
GV3	Audi	A1	Gasoline	DI	TWC	2016	Euro 6b	999	70
GV4	Opel	Astra	Gasoline	DI	TWC	2017	Euro 6b	999	77
GV5	VW	Golf BlueMotion	Gasoline	DI	TWC	2017	Euro 6c	1498	96
GV6	Lancia	Ypsilon	Gasoline	PFI	TWC	2016	Euro 6b	875	63
GV7	Renault	Clio	Gasoline	DI	TWC	2016	Euro 6b	1197	87
GV8	VW	Tiguan	Gasoline	DI	TWC+GPF	2018	Euro 6b	1395	110
GV9	Citroën	C3	Gasoline	PFI	TWC	2018	Euro 6d-TEMP	1199	61
PHEV	Mitsubishi	Outlander	Gasoline	PFI	TWC	2015	Euro 6b	1968	149
CNG-LCV	Fiat	Ducato	CNG	PFI	TWC	2018	Euro 6b	2999	100

Table 4. Diesel vehicle (DV) specifications.

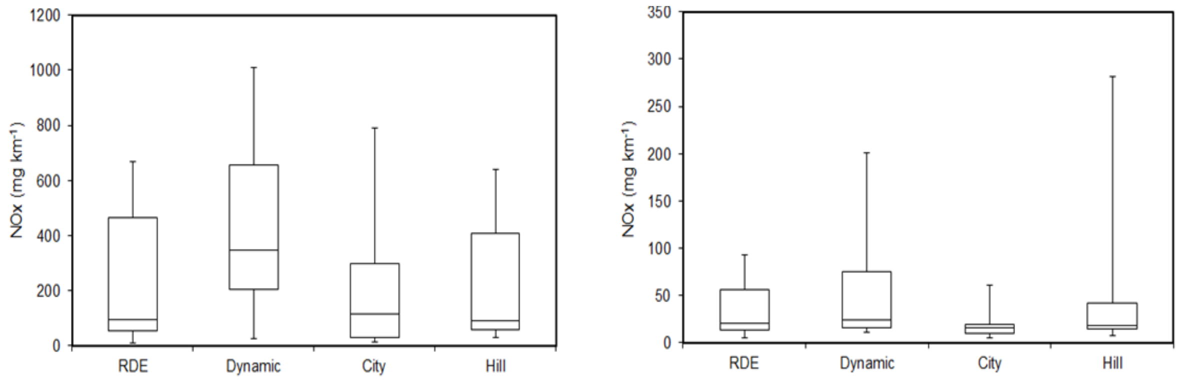
Code	Brand	Model	Fuel	Inj.	Emission Control system	Reg. Year	Euro standard	Engine Capty. (cm^3)	Power (kW)
DV1	Fiat	500X	Diesel	DI	DOC+EGR+DPF+LNT	2016	Euro 6b	1956	103
DV2	Peugeot	Partner	Diesel	DI	DOC+EGR+DPF+SCR	2017	Euro 6b	1560	73
DV3	Kia	Sportage	Diesel	DI	DOC+EGR+LNT+DPF	2017	Euro 6b	1685	85
DV4	VW	Golf BlueMotion	Diesel	DI	DOC+EGR+LNT+DPF	2015	Euro 6b	1968	110
DV5	BMW	530d - 5 series G30	Diesel	DI	DOC+ EGR+SCR+LNT+DPF	2017	Euro 6b	2993	195
DV6	Mercedes-Benz	C220d	Diesel	DI	DOC+ EGR+DPF+SCR	2017	Euro 6b	2143	125
DV7	Škoda	Superb	Diesel	DI	DOC+ EGR+DPF+SCR	2017	Euro 6c	1968	110
DV8	Peugeot	308	Diesel	DI	DOC+ EGR+DPF+SCR	2018	Euro 6d-TEMP	1499	96
DV9	Volvo	XC40	Diesel	DI	DOC+EGR+ DPF+LNT+SCR	2018	Euro 6d-TEMP	1969	140
DV10	Ford	Focus	Diesel	DI	DOC+EGR+LNT+DPF+LNT+pSCR	2018	Euro 6d-TEMP	1499	88

2.1 On-road emissions impact of driving dynamics and shares of operations

2.1.1 NOx emissions

The emissions factors indicated as RDE and Dynamic are the mean of the emissions obtained using routes RDE-1 and RDE-2 for the RDE compliant tests and the dynamic tests, respectively. Figure 2 illustrates NOx median emissions factors from diesel and gasoline vehicles obtained during the tests performed using the different routes and driving styles. Table 5 summarizes the NOx emission factors for each individual vehicle.

Figure 2. NOx median emissions factors from diesel (left plot) and gasoline (right plot) vehicles



Most gasoline vehicles complied with the NOx Euro 6d-TEMP on-road NTL (i.e., 60 mg/km multiplied by a conformity factor of 2.1) with the exception of GV8 during one of the dynamic tests (205 mg/km), the GV4 during the Hill route (288 mg/km). In addition, NOx emissions higher than the Euro 6d limits (60 mg/km multiplied by a conformity factor 1.43) were measured from GV7 during the Dynamic test (92 mg/km) and GV4 during RDE and Dynamic (91 and 93 mg/km respectively).

NOx median emissions factors from the diesel fleet (DV1 – DV10) were one order of magnitude higher than those of the gasoline fleet, and varied from ~92 mg/km, during the Hill and RDE compliant tests respectively, to 349 mg/km during the Dynamic tests. Individual average emission factors ranged from 9 mg/km (DV7) during the RDE test to 1011 mg/km (DV3) during the dynamic tests. The Euro 6b diesel vehicles DV1 – DV4 (type approved under the NEDC) tested under RDE compliant tests presented NOx emissions from similar (DV4) to up to 4 times higher than the diesel's RDE Euro 6d- TEMP (i.e., 80 mg/km multiplied by a conformity factor of 2.1) and 1.4 to 6 times higher than the RDE Euro 6d standard (i.e., 80 mg/km multiplied by a conformity factor of 1.43). Vehicle DV4 met the Euro 6d-TEMP tailpipe emissions requirements but it fell short of meeting Euro 6d. Vehicles DV5 and DV6 met the more stringent RDE Euro 6d. The elevated NOx emissions from Euro 6b vehicles could be explained by the after-treatment strategies and low efficiency of the catalytic systems used in those vehicles to reduce the emissions of NOx, namely SCR or LNT [Ko et al., 2017; O'Driscoll et al., 2016; 2018; Suarez-Bertoa et al., 2015b; 2016; 2017; Yang et al., 2015].

Table 5. Emission factors of NOx (mg/km) during the RDE, Dynamic (Dyn.), City-Motorway (City-MW) and Hill tests. The emissions factors presented in the columns RDE and Dyn. are the average of the emissions obtained along the two different routes (RDE-1 and RDE-2) tested using these two different driving dynamics (RDE and Dynamic)

	GV1	GV2	GV3	GV4	GV5	GV6	GV7	GV8	CNG-LCV
RDE	6	15	39	91	11	21	46	20	164
Dyn.	13	12	33	93	20	16	92	115	956
City-MW	9	11	21	62	5	-	18	16	242
Hill	8	19	56	288	10	-	25	18	515

	DV1	DV2	DV3	DV4	DV5	DV6	DV7	DV8	DV9	DV10
RDE	476	552	569	147	33	78	13	60	57	119
Dyn.	702	784	1005	645	85	300	39	188	319	338
City-MW	-	799	673	179	-	141	13	19	34	89
Hill	639	405	641	203	59	93	31	72	51	-

Vehicles DV8, DV9 and DV10 were type approved to the Euro 6 d-TEMP standard using WLTP and RDE tests. On the other hand, an RDE test was not required for vehicles DV5, DV6 and DV7 at the time of type approval. Nonetheless, together with the Euro 6d-TEMP vehicles (DV8 – DV10), they met the Euro 6d NOx tailpipe emissions requirements during the RDE, City and Hill tests. Only during the Dynamic tests, the NOx emission factors were higher than Euro 6 limits. Vehicles DV5 (during RDE-1-Dyn) and DV8 (during RDE-2-Dyn) were below the Euro 6d NOx requirements. Moreover, DV7 yielded very low emissions for this test (39 mg/km). This indicates that, although there is room for improvement, substantial progress has been made on NOx emission control in the more recent and that high reduction efficiency of NOx is often maintained beyond the dynamic boundaries of RDE. Vehicles DV7, DV8 and DV9 achieved lower NOx emissions compared to the Euro 6b diesel vehicles by using more advanced and complex catalytic systems (e.g., EGR + LNT + SCR, EGR + dual-LNT) and, possibly, a higher urea solution dosage in the SCR.

NOx emissions from the CNG-LCV were the highest recorded among the positive ignition vehicles (see Table 5). They ranged from 164 mg/km during the RDE route to 956 mg/km during the Dynamic routes, which is 9 times higher than the worst performing gasoline vehicle. It should be noted that this vehicle (CNG-LCV) was a light commercial vehicle whereas the other tested vehicles were passenger cars. Surprisingly, NOx emissions from the CNG-LCV were comparable to or higher than most of the diesel vehicles measured in this study. These high NOx emissions may be linked to lean engine operation.

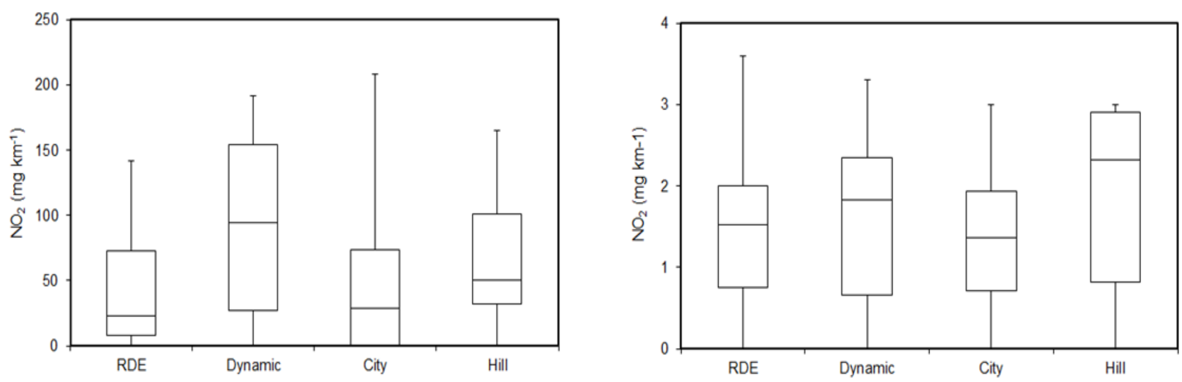
2.1.2 NO_2 emissions

Before the introduction of DPF and SCR systems, NOx in diesel exhaust was usually composed of >90% NO. However, to decrease soot oxidation temperatures for the DPF regeneration and since equimolar amounts of NO and NO_2 increase the reaction rate with NH_3 on the SCR, NO is oxidised to NO_2 on the DOC [Guan et al., 2014].

NOx emissions from the spark ignition vehicles tested were mainly composed of NO. Median NO_2 emissions from gasoline cars were very low (1 - 2 mg/km during all the tested routes with a maximum of 12 mg/km). On the other hand, median NO_2 emissions from diesel vehicles ranged from 23 to 94 mg/km, during the RDE and Dynamic routes respectively. Vehicles DV7 and DV8 emitted less than 5% of NOx as NO_2. Vehicles DV9 and DV10 had NO_2/NOx ratios (0.2) similar to those from Euro 6b vehicles.

Figure 3 illustrates NO_2 median emissions factors from diesel and gasoline vehicles obtained during the tests performed using the different routes and driving styles. Table 6 summarizes the NO_2 emission factors for each individual vehicle.

Figure 3. NO_2 median emissions factors from diesel (left plot) and gasoline (right plot) vehicles



The higher ratio of NO_2 emissions in the exhaust may have important effects on the urban atmospheric chemistry, and consequently on air quality. The EEA has recently reported that, following an increase of NO_2 emissions from diesel vehicles at the expense of NO, ground level ozone (O_3) concentrations have increased in several air quality measurement stations monitoring pollution from traffic in the EU [EEA, 2018].

Table 6. Emission factors of NO_2 (mg/km) during the RDE, Dynamic (Dyn.), City-Motorway (City-MW) and Hill tests. The emissions factors presented in the columns RDE and Dyn. are the average of the emissions obtained along the two different routes (RDE-1 and RDE-2) tested using these two different driving dynamics (RDE and Dynamic).

	GV1	GV2	GV3	GV4	GV5	GV6	GV7	GV8	CNG-LCV
RDE	0	3	1	2	1	0	1	2	15
Dyn.	0	3	0	3	2	0	2	7	33
City-MW	0	3	0	2	1	-	-	2	16
Hill	0	3	3	2	1	-	-	3	21

	DV1	DV2	DV3	DV4	DV5	DV6	DV7	DV8	DV9	DV10
RDE	131	124	127	42	7	22	1	6	13	27
Dyn.	176	125	190	157	10	104	2	14	40	110
City-MW	-	207	139	38	-	67	2	0	0	16
Hill	236	97	113	53	16	38	1	0	1	-

2.1.3 PN emissions

Figure 4 illustrates PN median emissions factors from diesel and gasoline vehicles obtained during the tests performed using the different routes and driving styles. Table 7 summarizes the PN emission factors for each individual vehicle.

PN emissions from diesel vehicles were below Euro 6 limits (6×10^{11} #/km) under all the studied conditions for all the studied vehicles even without using the applicable conformity factor of 1.5 for PN. PN median emissions ranged from 5×10^{9} #/km to 5×10^{10} #/km. There was no significant difference on PN emissions for the different routes used (see Figure 4). Although below Euro 6 limits, DV6 presented the highest PN emissions among the diesel vehicles (3.4-6.4 $\times10^{11}$ #/km), indicating lower filtration efficiency than the other tested vehicles. The measured PN emissions indicate an overall good performance of DPFs during real-world operation.

Figure 4. PN median emissions factors from diesel (left plot) and gasoline (right plot) vehicles

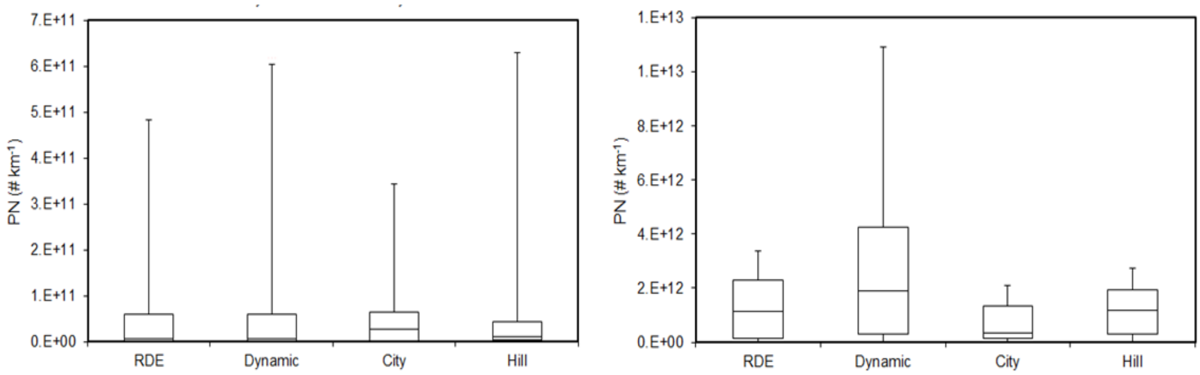


Table 7. Emission factors of PN ($\times 10^{11}$ #/km) during the RDE, Dynamic (Dyn.), City-Motorway (City-MW) and Hill tests. The emissions factors presented in the columns RDE and Dyn. are the average of the emissions obtained along the two different routes (RDE-1 and RDE-2) tested using these two different driving dynamics (RDE and Dynamic).

	GV1	GV2	GV3	GV4	GV5	GV6	GV7	GV8	CNG-LCV
RDE	6	2	12	24	0.9	21	31	0.2	6
Dyn.	11	4.5	28	34	1.2	104	62	0.3	-
City-MW	2.6	1.7	8.9	21	1.0	-	18	0.1	-
Hill	10	5.1	19	27	1.0	-	19	0.1	-

	DV1	DV2	DV3	DV4	DV5	DV6	DV7	DV8	DV9	DV10
RDE	-	-	0.03	-	0.17	5.0	0.06	0.7	0.02	0.03
Dyn.	-	-	0.01	-	2	6.1	0.20	0.7	0.06	0.07
City-MW	-	-	<0.01	-	-	3.4	0.30	0.6	<0.01	0.01
Hill	-	-	0.04	-	0.15	6.4	0.03	0.5	0.02	-

Missing emission factors are due to instrument failure or instrument unavailability in case of stand-alone system.

PN emissions from gasoline vehicles were up to three orders of magnitude higher than those obtained from diesel vehicles. Median PN emissions from gasoline vehicles varied from 3×10^{11} #/km to 2×10^{12} #/km. They are below the laboratory PN limit for GDIs until 2017 (6×10^{12} #/km), even without any additional margin. PN emissions from GDIs are higher due to the limited time available for fuel and air to be thoroughly mixed in the combustion chamber; these emissions increase during high-speed and sudden acceleration events due to rich air/fuel ratios [Überall et al., 2015; Yinhui et al., 2016]. On the other hand, PN emissions from PFI spark ignition vehicles are commonly linked to enrichment of the air-fuel mixture during cold start engine operations and accelerations. Although most of the GDIs studied here resulted in higher PN emissions than the PFIs, PN emissions from the PFIs exceed in some occasions the PN limits for diesel and GDI vehicles. High emissions of PFIs especially at dynamic cycles is not new [Giechaskiel et al., 2015; Suarez-Bertoa and Astorga, 2018].

The highest PN emissions were recorded for vehicle GV6, a PFI gasoline car, which not only exhibited very high PN emissions during the cold-start phase, but also across all trip sections. Emissions ranged from 2×10^{12} #/km during the RDE routes to 1×10^{13} #/km during the dynamic routes. The lowest PN emissions resulted from vehicle GV8 (1×10^{10} – 3×10^{10} #/km), a GDI vehicle equipped with a gasoline particle filter (GPF). Although this was the only gasoline vehicle equipped with a GPF, the consistency of the results with those from previous studies indicate that GDIs equipped with a GPF consistently achieve much lower PN emissions than those without the GPF [Joshi and Johnson, 2018]. It needs to be seen if future GPFs will be able to reach the emission levels of efficient DPFs (one order of magnitude lower).

PN median emissions were unsurprisingly higher – 2 times– during the dynamic routes (2×10^{12} #/km) than during the RDE routes (1×10^{12} #/km). More dynamicity means more accelerations episodes, which in turn results in richer air/fuel ratios, hence in higher PN emissions. PN median emissions were 3.5 times lower during the City-Motorway route than during the RDE ones. Excluding GV6 from the analysis (as it was not tested along this route), the PN median emissions are 2.4 times lower during the City-Motorway route than during the RDE. In any case, as illustrated in Figure 1, there were no significant differences on PN emissions for different routes. PFIs though had tendency for higher emissions during the Hill route.

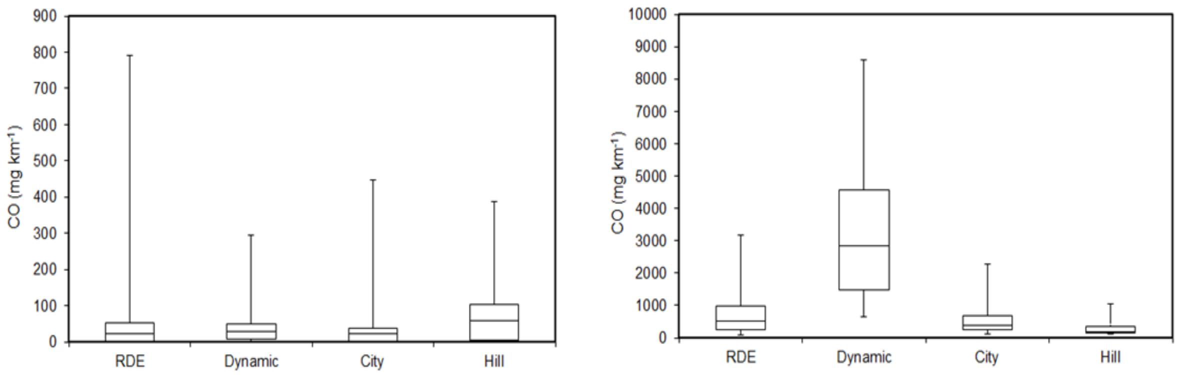
Due to an instrument failure, PN emissions from the CNG-LCV vehicle were only measured during the RDE tests. PN emissions were as high as those recorded from GDI vehicles reaching 1×10^{12} #/km during the RDE-1 route. PN average emission factor during the RDE routes was 6×10^{11} #/km. It should be noted that the specific vehicle had <3000km during the on road testing, so the contribution of fresh lubricant could be significant.

2.1.4 CO emissions

Figure 5 illustrates CO median emissions factors from diesel and gasoline vehicles obtained during the tests performed using the different routes and driving styles. Table 8 summarizes the CO emission factors for each individual vehicle.

CO emissions from diesel vehicles were below Euro 6 limits (500 mg/km) for all the studied vehicles and under all the studied conditions. Median CO emissions ranged from 20 and 41 mg/km. There was no significant difference on CO emissions for the different routes used (see Figure 5). The measured CO emissions indicate good performance of diesel oxidation catalysts (DOCs) during real-world operation.

Figure 5. CO median emissions factors from diesel (left plot) and gasoline (right plot) vehicles



CO Euro 6 emissions limit for gasoline light-duty vehicles is 1000 mg/km. CO median emissions from gasoline vehicles were one to two orders of magnitude higher than those obtained from diesel vehicles. Median CO emissions from gasoline vehicles ranged from 167 mg/km during the Hill test to 2850 mg/km during the dynamic test (see Figure 5). CO median emissions from gasoline emissions during dynamic tests were more than five times higher than those obtained during the RDE compliant tests.

Table 8. Emission factors of CO (mg/km) during the RDE, Dynamic (Dyn.), City-Motorway (City-MW) and Hill tests. The emissions factors presented in the columns RDE and Dyn. are the average of the emissions obtained along the two different routes (RDE-1 and RDE-2) tested using these two different driving dynamics (RDE and Dynamic)

	GV1	GV2	GV3	GV4	GV5	GV6	GV7	GV8	CNG-LCV
RDE	681	2192	208	990	317	988	433	161	307
Dyn.	2829	6234	1228	2577	864	7551	3303	2737	208
City-MW	370	2234	455	930	108	-	307	181	440
Hill	1046	450	167	199	115	-	127	149	317

	DV1	DV2	DV3	DV4	DV5	DV6	DV7	DV8	DV9	DV10
RDE	334	25	25	5	35	13	20	20	4	35
Dyn.	243	25	75	6	36	30	27	31	0	24
City-MW	-	32	34	9	-	21	30	0	0	56
Hill	205	129	103	4	57	4	65	25	0	-

Very high CO emissions were recorded for most gasoline vehicles during Dynamic trips, reaching concerning levels of 6000-8600 mg/km (see in particular GV2 and GV6); approximately 8 times more compared to the non-dynamic driving. For some vehicles they were associated to motorway operation during dynamic tests as well as RDE compliant test. These may be a consequence of an emissions strategy (AES) aiming to protect the TWC from overheating, but also may be due to an undersized catalyst. Since engine-out emissions were not measured during the testing campaign, it was not possible to examine the behaviour of the catalyst during these emission events. Further investigations will be conducted in future testing campaigns.

Regardless of its large engine displacement and high laden mass, the CNG-LCV exhibited the lowest CO emissions of all the positive ignition vehicles during the Dynamic tests, 208 mg/km. Nonetheless, CO emissions for this vehicle during the City-Motorway test (440 mg/km), were in agreement with the median of the other vehicles tested during City-Motorway (416 mg/km).

2.1.5 CO_2 emissions

Figure 6 illustrates CO_2 median emissions factors from diesel and gasoline vehicles obtained during the tests performed using the different routes and driving styles. Table 9 summarizes the CO_2 emission factors for each individual vehicle.

Median CO_2 emissions from diesel vehicles were slightly higher than median CO_2 emissions from the gasoline vehicles, contrary to normal expectation. Nonetheless, the vehicles tested presented in this study included several relatively small and lighter vehicles equipped with relatively small gasoline engines with average engine displacement of ~1150 cc and average power of ~75 kW. On the other hand, the average engine displacement and power of the diesel vehicles tested were ~1900 cc and ~112 kW. In addition, 5 out of 8 gasoline vehicles tested were GDIs, which are generally more efficient than PFIs.

Median CO_2 emissions increased for Dynamic trips in relation to RDE-compliant trip (+7% and +6% for gasoline and diesel, respectively). The highest impact of dynamic driving was measured for the CNG vehicle (+16%) which was also the heaviest vehicle. The City-Motorway driving resulted in lower CO_2 emissions compared to the RDE-compliant routes (-6% for both gasoline and diesel vehicles). The most energy-demanding route for diesel vehicles was the Hill route which on average resulted in 10% higher CO_2 emissions. In particular, this route was the most demanding for vehicles DV5 and DV6 (25% and 29% increase in CO_2 emissions, respectively). For gasoline vehicles, the Hill route exhibited 6% higher CO_2 emissions (average of all vehicles), with some gasolines vehicles (GV1 and GV5) achieving lower CO_2 emissions compared to RDE-compliant trips. It should be noticed that the Hill route begins and ends at the same point. Therefore, CO_2 emissions are the combination of and up-hill (Max. altitude ~1100m.a.s.l.) and downhill driving (Min. altitude ~200m.a.s.l.).

Figure 6. CO_2 median emissions factors from diesel (left plot) and gasoline (right plot) vehicles

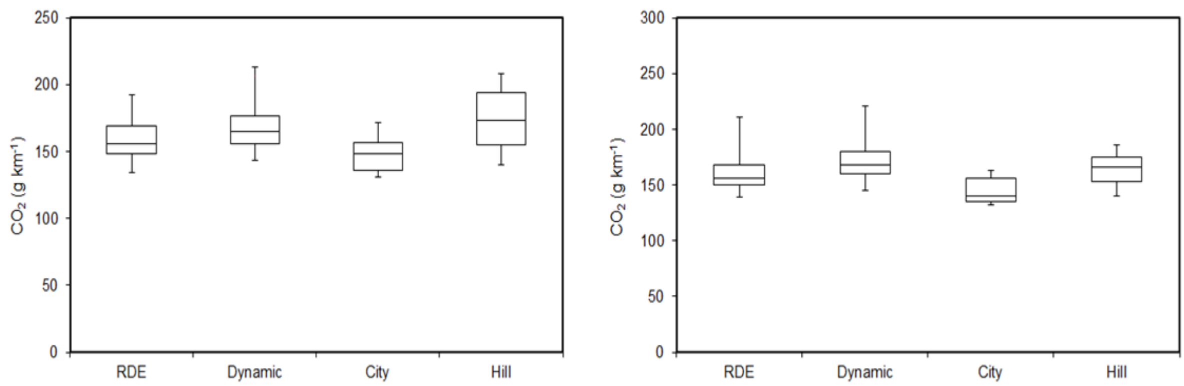


Table 9. Emission factors of CO_2 (g/km) during the RDE, Dynamic (Dyn.), City-Motorway (City-MW) and Hill tests. The emissions factors presented in the columns RDE and Dyn. are the average of the emissions obtained along the two different routes (RDE-1 and RDE-2) tested using these two different driving dynamics (RDE and Dynamic).

	GV1	GV2	GV3	GV4	GV5	GV6	GV7	GV8	CNG-LCV
RDE	155	156	129	140	154	201	166	172	243
Dyn.	167	152	149	164	168	215	180	184	282
City-MW	163	135	137	132	140	-	154	158	251
Hill	140	166	156	167	142	-	186	182	268

	DV1	DV2	DV3	DV4	DV5	DV6	DV7	DV8	DV9	DV10
RDE	188	139	155	158	156	150	152	139	188	169
Dyn.	203	154	165	173	177	162	153	150	209	162
City-MW	-	145	158	152	-	137	135	131	171	151
Hill	381	155	148	173	194	197	162	140	202	-

2.2 On-road emissions impact of sub-zero ambient temperatures and high altitude

Table 10, Table 11 and Table 11 summarize NOx, PN, CO and CO_2 emissions factors from the DV8, the GV9 and the PHEV obtained for the complete tests, the subsections urban, rural and motorway of the tests performed using the four different routes (RDE-1, RDE-2, Alpine-1 and Alpine-2).

2.2.1 *Emissions from a Euro 6d-TEMP diesel vehicle*

Criteria emissions (CO, NOx and PN) from the DV8 were higher at colder temperatures during on-road tests (Table 10). NOx raw emissions were always below Euro 6d-TEMP on-road emission requirement (80 mg/km + 2.1 conformity factor). The highest NOx emissions factors (113±4 mg/km) were obtained during Alpine-2, which was the most demanding test in terms of road grade, altitude and cold ambient temperature.

NOx emissions from the DV8 during the complete Alpine tests were 72±1 mg/km for Alpine-1 and 113±4 mg/km Alpine-2, up to 2 times higher than those measured during the RDE compliant routes (51±29 mg/km), performed at 24°C.

NOx emission factors in the urban section (~36 km long for all four routes) were always higher than those obtained during the urban and motorway sections and ranged from 67±45 mg/km in the RDE-routes to 169±14 mg/km in the Alpine-2 (see Table 10). NOx emission factors during the motorway section were 70 – 90 mg/km for the Alpine routes and 50±30 mg/km for the RDE-routes.

Wang et al. (2018) reported higher emissions of CO and PN at higher altitude for a vehicle certified under China IV standard tested on-road at 30-2990 m.a.s.l. at 33-25°C. However, absolute CO and PN emissions for the vehicle were low. PN and CO emissions from diesel vehicles have been shown to be little affected by cold ambient temperatures [Suarez-Bertoa and Astorga, 2018].

Although PN emissions from the DV8 were higher during the cold and high altitude tests than during moderate conditions, they were relatively low (<6×10^{11} #/km Euro 6 limit) during all the tests performed. PN emission factors ranged from 1×10^{11} #/km during the RDE compliant routes (RDE-routes) to 2×10^{11} #/km during Alpine-1.

Table 10. DV8's emission factors of NOx (mg/km), PN (#/km), CO (mg/km) and CO_2 (g/km) during the RDE, Dynamic (Dyn.), City-Motorway (City-MW) and Hill.

	DV RDE-routes				**DV** Alpine-1				**DV** Alpine-2			
	Comp.	**Urb.**	**Rur.**	**MW**	**Comp.**	**Urb.**	**Rur.**	**MW**	**Comp.**	**Urb.**	**Rur.**	**MW.**
NOx	51	67	28	50	72	99	30	71	113	169	65	78
PN $\times10^{11}$	1.3	1.3	2	1.2	2.0	1.9	2.3	1.9	1.3	1.2	1.6	1.3
CO	41	74	21	15	83	136	52	39	149	255	72	68
CO_2	134	136	115	145	134	129	117	157	143	138	124	168

Testing on higher positive road grade leads to faster heating of the DOC, and therefore higher efficiency of the catalyst to reduce CO emissions. In fact, CO emissions measured from the DV were relatively low during all the on-road tests. Emission factors during the urban section ranged from 74 mg/km (RDE-routes) to 255 mg/km (Alpine-2). The CO emissions measured for the DV8 during the Alpine tests were in line with those reported for Euro 6b vehicles tests at -7°C using the WLTP [Suarez-Bertoa and Astorga, 2018].

Average CO_2 emissions from the DV8 at cold temperatures and high altitude of the Alpine-1 route were comparable to the RDE-routes and 7% higher during Alpine-2 than during the RD-routes.

2.2.2 *Emissions from a Euro 6d-TEMP gasoline vehicle*

NOx emissions from the GV9 were higher at colder temperatures. NOx emissions from the GV9 were surprisingly high during the Alpine tests, performed at -5°C – -8°C and during the test performed using the RDE compliant route, RDE-2. The emissions during the complete on-road tests were 113 – 178 mg/km. It should be noted that this are raw emissions and the correction factor (1.6) for extended conditions was not applied. Previous studies have shown that cold ambient temperatures lead to higher NOx emissions from gasoline vehicles as the light-off of the TWC takes longer at colder temperatures [Suarez-Bertoa and Astorga, 2018 and references therein]. Interestingly, urban emissions during Alpine-1, performed at -5°C, were low (44 mg/km), indicating that, for this vehicle, cold temperature or high altitude did not have a strong impact on the NOx emissions (Table 11).

NOx emissions during the urban section of Alpine-2 (170 mg/km), which starts with a steep slope, and during the motorway sections of Alpine-1 (367 mg/km) and Alpine-2 (290 mg/km), which faced certain length uphill (but also downhill), were ~8 times higher than during the urban section of RDE-routes (47 mg/km) and Alpine-1 (44 mg/km), which are relatively flat. This indicates that road grade may have a strong impact on the NOx emissions of this vehicle.

PN emissions for the GV9 were relatively high during most tests (7 – 8 ×10^{11} #/km during the RDE-routes, Alpine-1) and very high during Alpine-2 (1.4×10^{12} #/km). The urban section of the on-road routes presented the highest emission factors, ranging from 1.1×10^{12} #/km during Alpine-1 to 2.3×10^{12} #/km during Alpine-2. High PN emissions from PFI during cold temperature tests has been previously reported for laboratory studies [Suarez-Bertoa and Astorga, 2018; Zhu et al., 2017]. High PN emissions from PFI vehicles at cold temperature are linked to enrichment of the air-fuel mixture during cold-start engine operation, which compensates for the reduced fuel vaporization and elevated friction of engine components, leading to incomplete fuel combustion. Moreover, at low ambient temperature, catalytic after-treatment systems need longer to reach their light-off temperature. PN emissions decrease as the engine gets warmer due to better combustion. However, PN emissions from the GV9 were high during the motorway section, when the catalyst should have reached the required operating temperature.

Table 11. GV9's emission factors of NOx (mg/km), PN (#/km), CO (mg/km) and CO_2 (g/km) during the RDE, Dynamic (Dyn.), City-Motorway (City-MW) and Hill.

	GV RDE-routes				**GV** Alpine-1				**GV** Alpine-2			
	Comp.	**Urb.**	**Rur.**	**MW**	**Comp.**	**Urb.**	**Rur.**	**MW**	**Comp.**	**Urb.**	**Rur.**	**MW.**
NOx	113	47	42	88	176	44	138	367	178	170	91	290
PN ×10^{11}	8	13	4	4	6.6	11	3	4	14	23	6	9
CO	125	215	45	127	135	261	40	57	155	265	64	73
CO_2	149	167	114	157	150	166	110	163	152	158	131	167

It is should be noticed that, at the time being, PN emissions from PFI vehicles are only regulated in China under China-6 regulation [China 6].

CO emissions from the GV9 were low during all the performed tests. CO emissions were comparable at the two studied temperatures and the other studied conditions. They ranged from 125 mg/km during the RDE-routes to 155 mg/km during Alpine-2. Although CO urban emission factors during the on-road test were two times higher than those obtained from the complete tests, they were relatively low (215 – 261 mg/km).

CO_2 emission factors during the cold and high altitude tests (Alpine-1 150 g/km and Alpine-2152 g/km) were comparable to the tests performed in along the RDE compliant routes (1490 g/km). In previous laboratory studies performed using the WLTP it was reported a ~16% increase on CO_2 emissions as the temperature decreased from 23°C to -7°C [Zhu et al., 2017; Suarez-Bertoa and Astorga, 2018].

2.2.3 *Emissions from a Euro 6b gasoline plug-in hybrid vehicle*

The ambient temperature together with the use of the PHEV's heating system affected dramatically the use of the internal combustion engine (ICE) of the vehicle and consequently its emissions. During all the Alpine tests, where temperature was below -5°C, and when the heating system was activated, the ICE started as soon as the heating was enable, i.e., as soon as the test initiated (see Figure 7). The activation of the ICE was dependent of the ambient temperature. In fact, during RDE-routes the vehicle ran electric for ~1000s, even though the air-conditioning system was activated as soon as the car was ignited.

NOx emissions from the PHEV were very low (<9 mg/km) in most of the studied conditions (maximum NOx 33 mg/km during the Alpine-2). NOx emissions were comparable during the RDE compliant routes performed at 9°C (4 mg/km) and the Alpine-1 (performed at -5°C; 5 mg/km), which indicates that cold temperature and the maximum allowed altitude of RDE (1300m) did not appear to affect these emissions (Table 11). Similar as for the GV9, the highest NOx emissions were measured during the Alpine-2, which is the most demanding in terms of temperature, torque, and altitude. NOx emission factors during the urban section were also low (up to 32 mg/km).

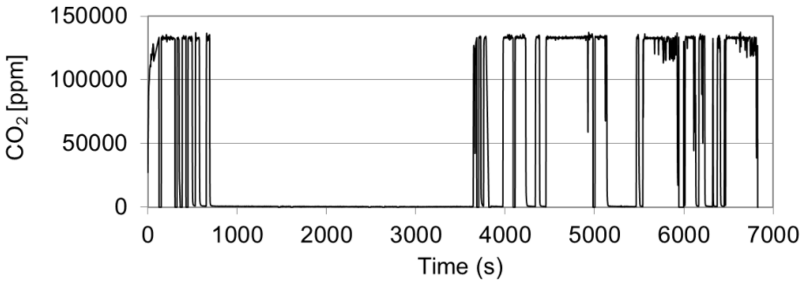
While the Alpine-1 test yielded the highest CO emissions (1767 mg/km), the highest PN emissions were measured during the Alpine-2 test (1.0×10^{12} #/km). However, the lowest CO emissions were measured during the Alpine-2 test (1010 mg/km) and the lowest PN emissions during the Alpine-1 test (3.5×10^{11} #/km).

When the use of the heating system along the Alpine routes was taken into consideration, it was recorded that CO and PN emissions were approximatively three times higher when the heating system was disabled than when it was enabled (Table 12).

The highest CO emissions (3153 mg/km) were measured during Alpine-1 AUX-OFF, and the lowest during Alpine-2 AUX-ON (1010 mg/km). The highest PN emissions (3.2×10^{12} #/km) were measured during Alpine-2 AUX-OFF, and the lowest during Alpine-1 AUX-ON (3.5×10^{11} #/km).

Figure 7. CO_2 emission profile during the Alpine-1 tests performed with the PHEV at 12% battery state of charge (SOC) and with the air conditioning heating system enabled (AUX-ON) and disabled (AUX-OFF). CO_2 emissions are an indicator of the ICE operation.

Alpine-1 AUX-ON



Alpine-1 AUX-OFF

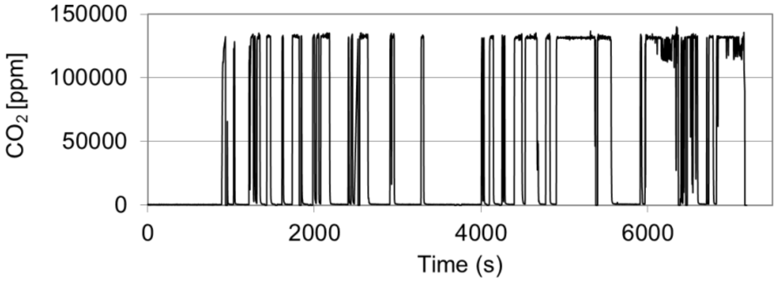

150000
100000
50000
0
CO2 [ppm]
0
2000
4000
6000
Time (s)

Table 12. PHEV's emission factors of NOx (mg/km), PN (#/km), CO (mg/km) and CO_2 (g/km) during the RDE, Dynamic (Dyn.), City-Motorway (City-MW) and Hill.

	PHEV RDE-routes				**PHEV** Alpine-1				**PHEV** Alpine-2			
	Comp.	**Urb.**	**Rur.**	**MW**	**Comp.**	**Urb.**	**Rur.**	**MW**	**Comp.**	**Urb.**	**Rur.**	**MW.**
NOx	4	1	2	2	5	7	1	4	33	32	35	33
PN $\times 10^{11}$	9	9	3.3	4	3.5	4.9	3	2.1	10	14	10	3.9
CO	1375	370	362	2477	1767	842	817	3710	1010	1090	630	1266
CO_2	152	82	159	220	140	89	143	203	174	183	146	188

The difference between AUX-OFF and AUX-ON on the CO and PN emissions was also observed during the laboratory tests using the WLTP at -7°C. As described in a previous study with other two PHEVs investigated in the laboratory at different conditions [Suarez-Bertoa et al., 2019], this difference may be linked to the way the engine and TWC are heated during the two different operations. When the heating system is enabled, the ICE initiate with the vehicle stopped and allows the engine and TWC to heat up on a more controlled manner during low load operations (similarly to a conventional vehicle). On the other hand, when the heating system is disabled the ICE kicks in at higher loads, while the vehicle is already running. The combination of the high load and cold engine/catalyst may result on incomplete combustion, i.e., high emissions of particles and CO, that a catalyst that has not reach light-off is not capable of reducing.

Table 13. PHEV's emission factors of NOx (mg/km), CO (mg/km), PN (#/km), CO_2 (g/km), for the complete on-road tests, their sections (urban, rural and motorway (MW)) during the Alpine-1 and Alpine-2 tests performed with the PHEV at 12% battery SOC and with the air conditioning heating system enabled (AUX-ON) and disabled (AUX-OFF).

	PHEV Alpine-1 –AUX-ON				**PHEV** Alpine-1 – AUX-OFF			
	Comp.	**Urban**	**Rural**	**MW**	**Comp.**	**Urban**	**Rural**	**MW**
NOx	5	7	5	4	1	0	0	2
PN $\times 10^{11}$	3.5	4.9	3.5	2.1	6.5	12	3.0	2.5
CO	1767	842	1767	3710	3153	559	799	7935
CO_2	140	89	140	143	148	97	136	215

	PHEV Alpine-2 –AUX-ON				**PHEV** Alpine-2 – AUX-OFF			
	Comp.	**Urban**	**Rural**	**MW**	**Comp.**	**Urban**	**Rural**	**MW**
NOx	33	32	35	33	9	1	12	18
PN $\times 10^{11}$	10	14	10	3.9	32	36	37	22
CO	1010	1090	630	1266	2627	1916	1020	5082
CO_2	174	183	146	188	164	168	105	211

3 Conclusions

Our results indicate that, following the introduction of the RDE procedure in EU, more efficient and complex emission control are being used to reduce the emissions of the pollutants, particularly NOx, from diesel vehicles. Consequently, the selected diesel vehicles exhibit markedly lower NOx emissions than earlier Euro 6 diesel vehicles for the RDE-compliant tests and for some of the most demanding tests outside RDE boundary conditions. This is a promising indication of the capability of RDE-compliant vehicles (Euro 6d-TEMP and later) to deliver consistently low-NOx emission performance. Nonetheless, during the Dynamic tests the NOx emission factors were higher than Euro 6 limits even for some Euro 6d-TEMP diesel vehicles and gasoline vehicles studied.

CO emissions from gasoline vehicles during dynamic tests were more than five times higher than those obtained during the RDE compliant tests. This indicates some of the limitations of the current procedure, which does not include measuring CO.

PN emissions from gasoline vehicles (including PFIs) were up to three orders of magnitude higher than those obtained from diesel vehicles. PN median emissions were two times higher during the dynamic routes (2×10^{12} #/km) than during the RDE routes (1×10^{12} #/km).

Tests performed at cold ambient temperature and high altitude, outside the RDE boundary conditions, resulted in higher emission of NOx and CO than those obtained when vehicles were tested on RDE compliant routes and moderate conditions of temperature and altitude. Nonetheless, the two Euro 6d-TEMP vehicles tested in those extreme conditions yielded NOx emissions factors that fulfilled the Euro 6d-TEMP emission requirements.

Raw emissions of criteria pollutants from the Euro 6d-TEMP vehicles were below Euro 6d-TEMP on-road emission requirements even when considering the fact that the correction for RDE extended conditions (1.6 factor) was not applied. Our Alpine tests were performed entirely at RDE extended conditions (or beyond) for both altitude and temperature.

The ambient temperature together with the use of the PHEV's heating system affected dramatically how the ICE is used and the emissions vehicle. Although NOx emissions (4 – 33 mg/km) from the PHEV, a PFI vehicle Euro 6b compliant, were low at all the studied conditions, CO (1010 – 1849 mg/km) and PN (3.5×10^{11} – 1.0×10^{12} #/km) emissions were high in most cases.

Emission factors obtained in this study will allow updating current vehicle emissions inventories providing real world emissions of pollutants, that in some cases (CO and PN from PFI) is rather limited in the literature. Moreover, the study presents the first results of vehicles type-approved under the most stringent emission standards at the moment (Euro 6d-TEMP) investigated under different real-world driving situations.

3.1 Recommendations

- Our work underlines the urgent necessity of a technology- and fuel-neutral approach to vehicle emission standards, whereby all vehicles must comply with the same emission limits for all pollutants.
- CO and PN emissions from PFI gasoline vehicles are not regulated currently by RDE. However, it has been shown that their emissions can be high. Therefore, it is advisable to include them along with NOx in the RDE procedure.
- Correction factor for RDE extended conditions (1.6 dividing factor) is not shown to be necessary.

Summary of the outcomes

Box 3. Summary of the outcomes.

1. On road emissions of NOx, PN, NO_2, CO and CO_2 from nineteen Euro 6b+ vehicles, including diesel (3 of which Euro 6d-temp) gasoline (GDI and PFI) and CNG vehicles, were investigated following RDE standard procedure and other real world operations not covered by the RDE (dynamic driving style, different shares of operation) using 4 different routes.

○ Euro 6d-TEMP diesel vehicles exhibit markedly lower NOx emissions than earlier Euro 6 diesel vehicles for the RDE-compliant tests and for some of the more demanding tests outside RDE boundary conditions.

o When equipped with a GPF, GDI cars can meet RDE requirements for PN on-road emissions.

o Tests outside RDE boundary conditions have shown potential emissions related issues:

o Gasoline PFI vehicles can present high PN emissions during RDE tests;

o Gasoline cars often presented high CO emissions during dynamic RDE tests;

o When driven outside the RDE dynamicity boundaries:

- o NOx emissions increased for diesel cars, including Euro 6d-TEMP;
- o NOx emissions from some gasoline cars were higher than the Euro 6 limit (60mg/km x CF 2.1);
- o PN emissions from gasoline cars were higher than $6x10^{11}$#/km (except for the GPF-equipped car).

2. On-road emissions of NOx, CO, PN and CO_2 from two Euro 6d-TEMP certified vehicles, one diesel (DV8) one gasoline (GV9), and one Euro 6b plug-in hybrid vehicle (PHEV) were investigated at sub-zero ambient temperatures and high altitudes.

o Emissions were higher at cold temperature and high altitude (>1300m) than at RDE moderate temperature and altitude conditions.

o Ambient temperature together with the use of the heating system of the PHEV's strongly and negatively impacted the emissions of CO and PN.

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List of abbreviations

AES	Auxiliary Emissions Strategy
CI	Compressed Ignition
CNG	Compressed natural gas
CNG-LCV	Compressed natural gas-Light commercial vehicle
CVS	Constant Volume Sampler
CVS 75	Constant Volume Sampling 75
DOC	Diesel Oxidation Catalyst
DPF	Diesel Particle Filter
EGR	Exhaust Gas Recirculation
ERMES	European Research for Mobile Emission Sources
FTP	Federal Test Procedure
GDI	Gasoline Direct Injection
GPF	Gasoline Particle Filter
HC	Hydrocarbons
LNC	Lean NOx Catalyst
NMHC	Non-Methane Hydrocarbons
NTE	Not-To-Exceed Limit
PFI	Port Fuel Injection
PHEV	plug-in hybrid vehicle
PI	Positive Ignition
PN	Particle Number
pSCR	Passive Selective Catalyst Reaction
RDE	Real Driving Emission
SCR	Selective Catalyst Reaction
SOC	State Of Charge
THC	Total Hydrocarbons
TWC	Three Way Catalyst
UDC	Urban Driving Cycle
WHO	World Health Organization

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Annexes

Annex 1. Measurements

The vehicles used in this study were selected to be a representative sample of the European market for new vehicles. The tested fleet included some of the best-selling models from different manufacturers across vehicle segments and engine sizes. The vehicles were equipped with the usual exhaust after-treatment technologies in the EU for new cars sold between 2016 and 2018. Gasoline vehicles used either port fuel injection (PFI) or direct injection (GDI) technology. One gasoline vehicle (GV8) was equipped with a gasoline particulate filter (GPF). All diesel vehicles were equipped with an exhaust gas recirculation (EGR) system and either a lean NOx trap (LNT), selective catalytic reduction (SCR) or both (DV9) to control NOx emissions. One diesel vehicle (DV10, type-approved to Euro 6d-TEMP) was equipped with a dual LNT and a passive SCR (not requiring urea solution refills).

All vehicles were tested using the applicable laboratory procedures for exhaust emissions, i.e., WLTP [EU 2017/1151] for vehicles DV8, DV9 and DV10, and Type 1 test according to UNECE Regulation 83 for all others (see [Clairotte et al, 2018; Suarez-Bertoa and Astorga 2018] for a complete description of the tests). The corresponding Euro 6 limits were met in all cases. Compliance with the emission limits over the laboratory test was taken as indication that the vehicles were free of malfunctions that could result in abnormally high emissions.

The measurement of the instantaneous, on-road emissions of NOx, NO_2, CO, PN and/or CO_2 were performed using PEMS. Vehicle DV1 and PHEV were tested using a Semtech Ecostar system (Sensors, Saline, Michigan, USA – model 2013), and all other vehicles were tested using an AVL MOVE system (AVL, Graz, Austria – model 2016). Both PEMS systems consist of a tailpipe attachment, heated exhaust lines, an exhaust flow meter (EFM), exhaust gas analyzers, a solid particle counter, data logger connected to vehicle network, a GPS and a weather station for ambient temperature and humidity measurements. Both systems measure exhaust gas concentrations of CO and CO_2 by a non-dispersive infrared sensor, and NO and NO_2 by a non-dispersive ultra-violet sensor. NOx is calculated by the sum of the concentrations of NO and NO_2. PN was measured by means of diffusion charge methodology using the MOVE (GV5-GV9, DV3, DV7-DV10) or by condensation particle counter (CPC) using a TSI NPET 3795, modified by HORIBA to reach higher concentrations (GV1-GV4, DV1, DV2, DV4 – DV6, CNG-LCV and PHEV). A stand-alone Testo3 analyser (NanoMet3), which also measures PN means of diffusion charge methodology, was used for the PHEV during Alpine-1 and Alpine-2 tests. EFM uses a Pitot tube to calculate flow rate. All relevant emissions data were recorded at a frequency of 1 Hz. The PEMS used in the described experimental campaign are routinely validated on the chassis dynamometer as recommended by RDE regulation.

The emission factors reported here were calculated by integrating the total mass emissions measured during the test and dividing the obtained value by the driven distance, as estimated from the GPS velocity signal. These are the so-called 'raw' emissions (without using the weighting function based on CO_2 emissions as introduced in the fourth package of the RDE regulation) [EU 2018/1832].

The PHEV was tested along Alpine-1 and Alpine-2 activating and deactivating the air heating system (set in automatic mode at 21°C when activated; hereinafter, A/C-ON and A/C-OFF, respectively). For PHEV, RDE-routes was only performed using the air heating system.

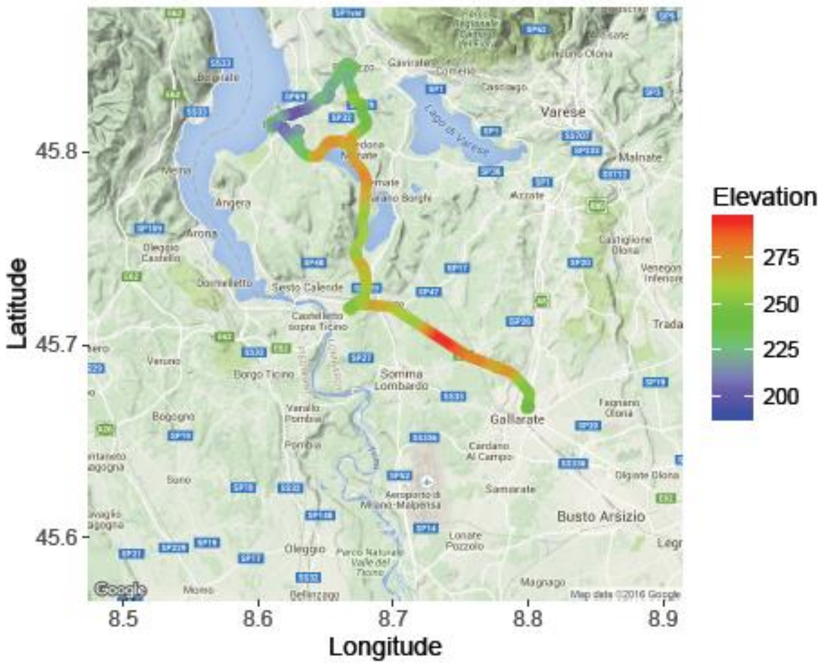
Annex 2. Routes

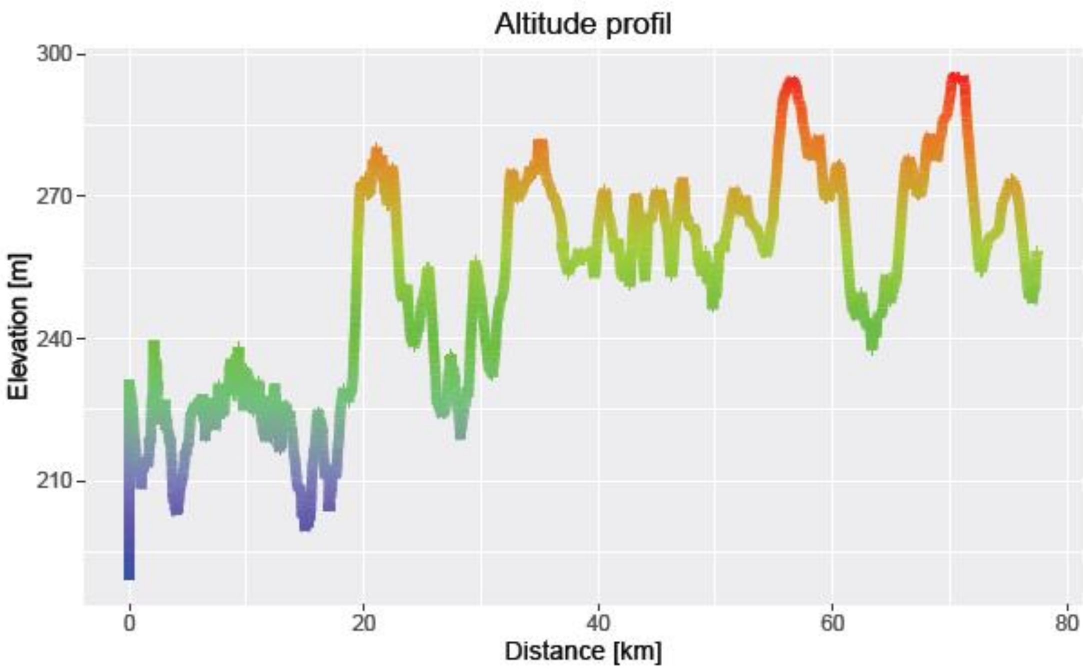
Table 2 summarizes the main characteristics of the routes used. Route RDE-1 and Route RDE-2 were designed to fulfil all the requirements of the RDE procedure. Route City-Motorway presents a different sequence of vehicle operation (City-Motorway-City-Motorway-City instead of the usual urban-rural-motorway), and urban and motorway shares are longer than allowed by RDE. Route Hill has a positive altitude gain outside RDE boundaries (~1800m), and it comprises only urban operation.
Vehicles were tested fulfilling RDE requirements along route RDE-1 and route RDE-2. Then, they were tested through the two same routes using a more dynamic driving style (i.e., seeking an increase in the 95th percentile of $v*a$). Even if dynamic tests presented higher $v*a$, some of these tests fulfilled the Max. 95th percentile of $v*a$ RDE boundary. The higher dynamicity was achieved for example by faster starts after fully stopping the vehicle at traffic lights or engaging lower gears when using manual transmission. All the dynamic tests were performed respecting the traffic code.

For the tests performed in the Alpine area, Alpine-1 fulfils all the requirements of the RDE procedure with the exception on the maximum altitude, which is slightly above (aprox. 1380m) the maximum allowed for an RDE test, 1300m. Alpine-2 fulfils some of the requirements of the RDE procedure such as: section sequence (urban, rural and motorway), share of operation, driving dynamics, among others, but explores altitudes (Max. 2000 m) and positive altitude gain (>1200m/100km) outside RDE boundaries.

Route# 1 – RDE-1

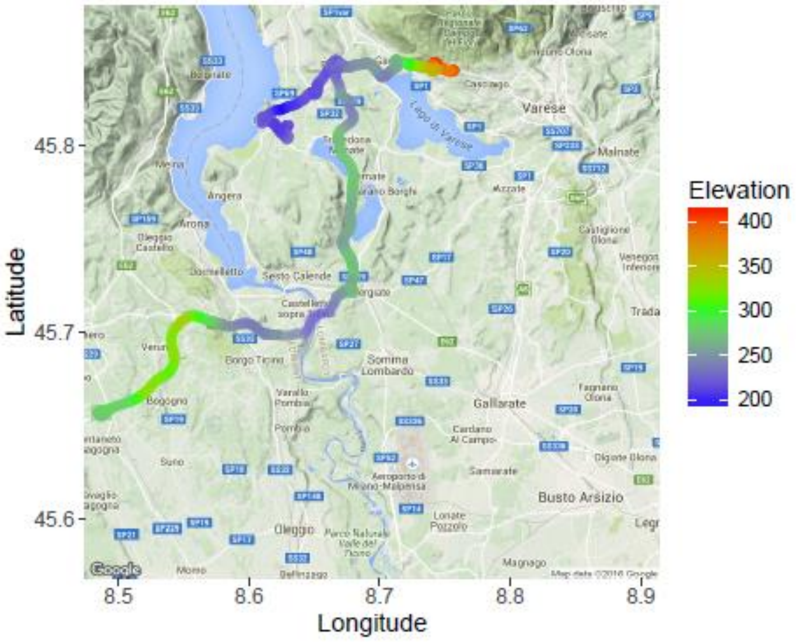
Total Distance [km]	Ca. 79
Urban Rural Motorway Distance Shares [%]	38.5 – 27.5 – 34.0
Average speed [km/h]	48.8
Average urban speed [km/h]	27.5
Cumulative altitude gain [m/100km]	631

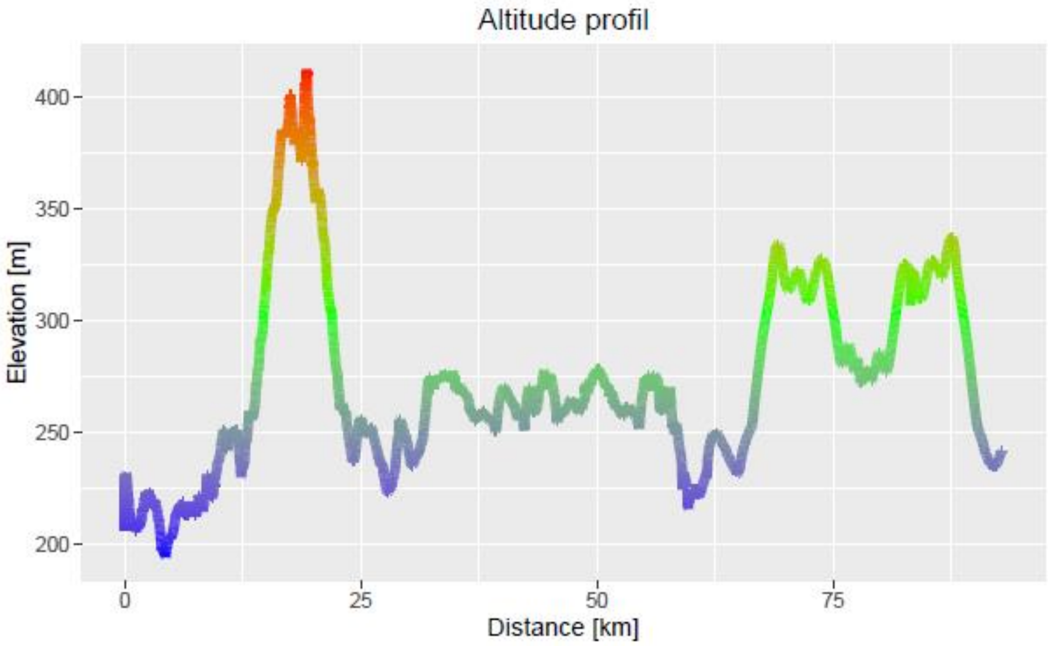




Route# 2 – RDE-2

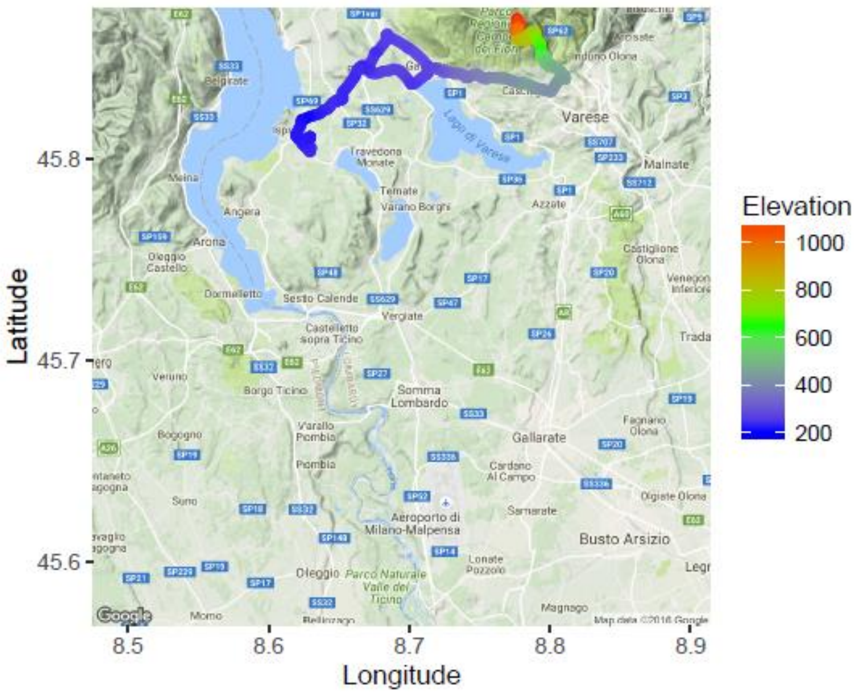
Total Distance [km]	Ca. 94
Urban Rural Motorway Distance Shares [%]	36.7 – 25.7 – 37.6
Average speed [km/h]	51.0
Average urban speed [km/h]	27.5
Cumulative altitude gain [m/100km]	739

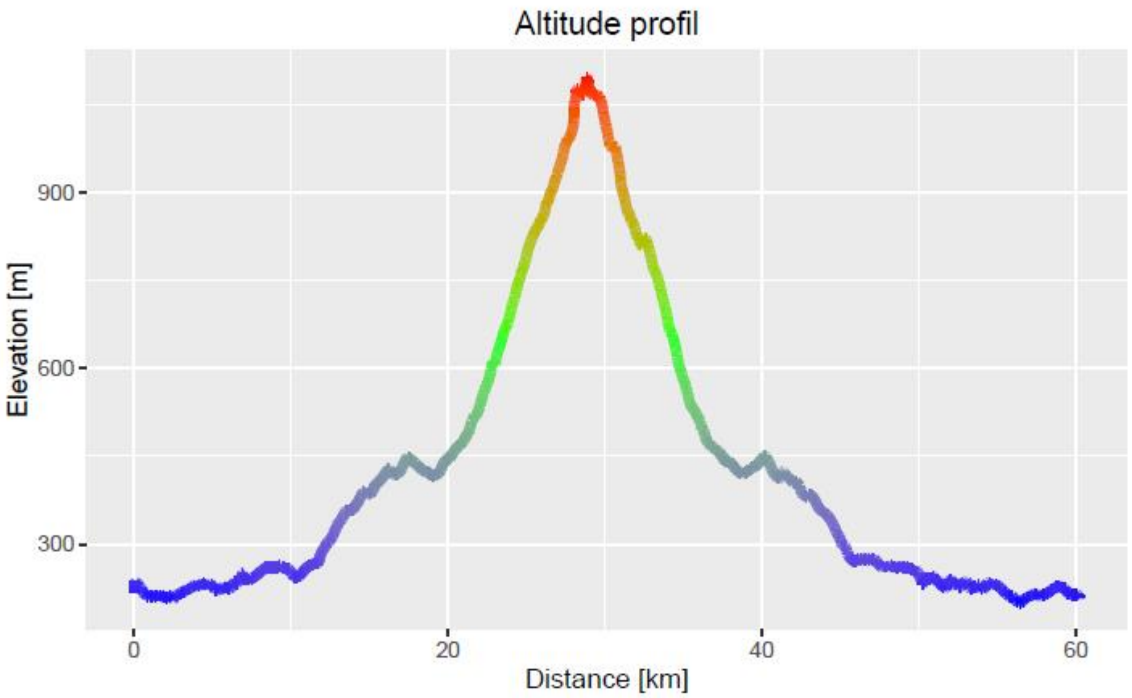




Route# 3 - Hill

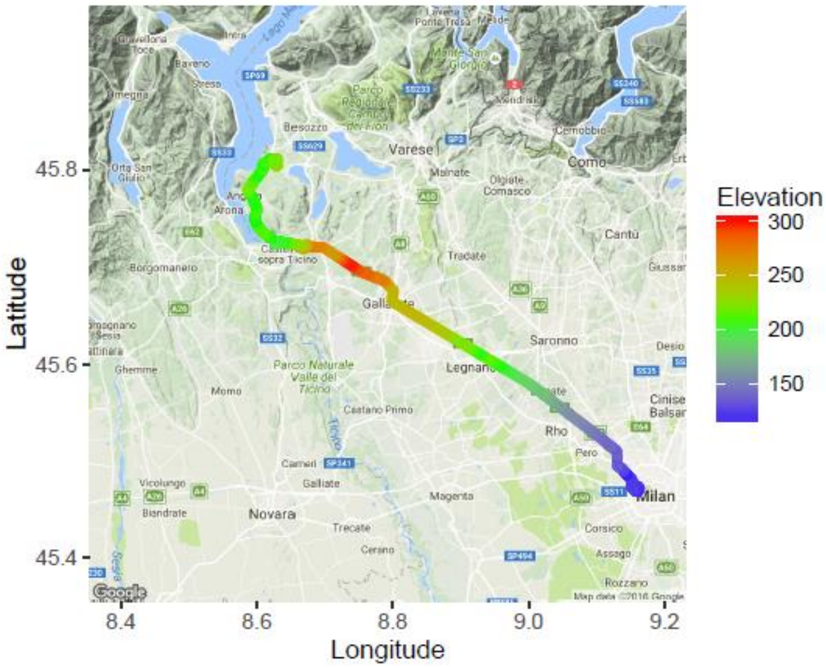
Total Distance	Ca. 62
Urban Rural Motorway Distance Shares [%]	95.5 – 4.5 – 0%
Average speed [km/h]	34.5
Average urban speed [km/h]	33.8
Cumulative altitude gain [m/100km]	1800

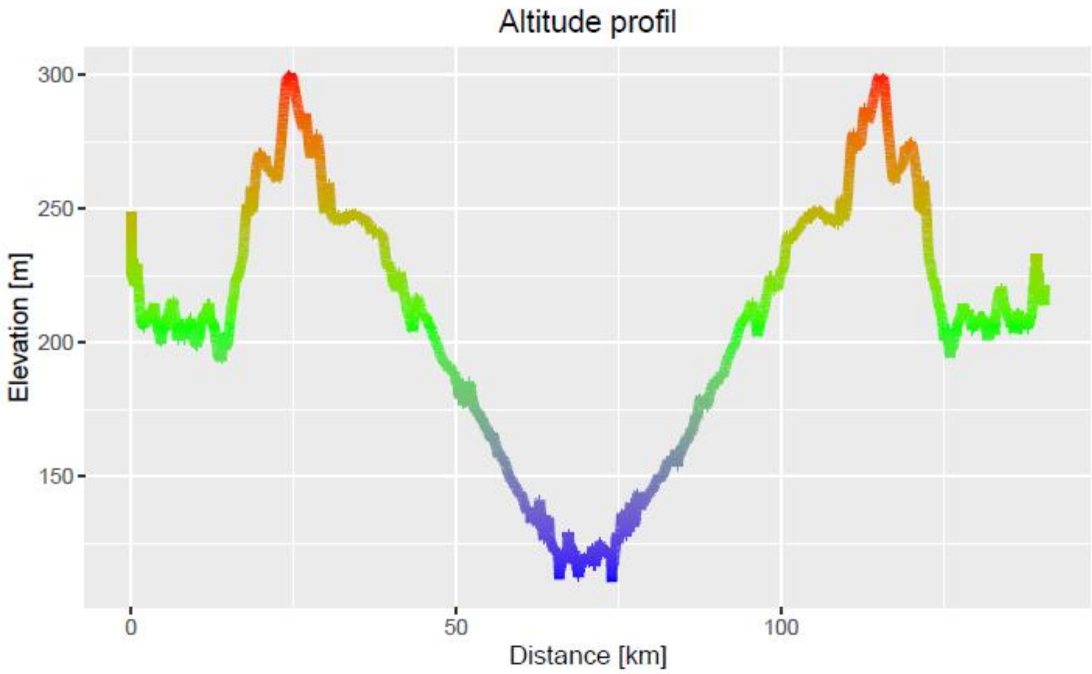




Route# 4 – City-Motorway

Total Distance	Ca. 141
Urban Rural Motorway Distance Shares [%]	30.1 – 13.7 – 56.2
Average speed [km/h]	60.3
Average urban speed [km/h]	30.9
Cumulative altitude gain [m/100km]	374





Annex 3. Emission Factors

Emission factors of NOx (mg/km), NO_2 (mg/km), CO (mg/km), CO_2 (g/km) and PN (#/km) for the tested vehicles D1-D10, GV1-GV8 and CNG during the complete on-road tests (C.) and the sub-sections: urban (U.), rural (R.) and motorway (MW).

DV1

	RDE-1					**RDE-2**					**RDE-1-Dyn**					**RDE-2-Dyn**					**City-MW**					**Hill**
	C.	**U.**	**R.**	**MW**		**C.**	**U.**	**R.**	**MW**		**C.**	**U.**	**R.**	**MW.**		**C.**	**U.**	**R.**	**MW.**		**C.**	**U.**	**R.**	**MW.**		**C./Urb**
NOx	474	279	385	869		477	296	336	872		646	525	494	973		759	523	433	1326							639
NO_2	120	90	127	157		141	113	140	178		187	149	157	269		165	156	130	207							236
CO	262	258	151	409		405	349	235	666		298	378	266	228		188	197	104	256							205
CO_2	187	220	143	196		189	218	135	210		204	257	150	197		202	229	145	223							381
PN $\times 10^{11}$																										

DV2

	RDE-1					**RDE-2**					**RDE-1-Dyn**					**RDE-2-Dyn**					**City-MW**					**Hill**
	C.	**U.**	**R.**	**MW**		**C.**	**U.**	**R.**	**MW**		**C.**	**U.**	**R.**	**MW.**		**C.**	**U.**	**R.**	**MW.**		**C.**	**U.**	**R.**	**MW.**		**C./Urb**
NOx	483	260	525	775		620	472	515	884		628	392	679	886		939	682	872	1252		799	810	615	837		405
NO_2	108	97	151	74		139	186	190	42		94	125	101	46		155	213	190	71		207	466	191	58		97
CO	30	63	10	2		20	40	4	7		38	48	37	28		12	22	2	10		32	81	19	5		129
CO_2	134	151	106	141		144	152	108	163		153	169	136	153		155	167	131	160		145	157	118	145		155
PN $\times 10^{11}$																										

DV3

	RDE-1				RDE-2				RDE-1-Dyn				RDE-2-Dyn				City-MW				Hill
	C.	**U.**	**R.**	**MW**	**C.**	**U.**	**R.**	**MW**	**C.**	**U.**	**R.**	**MW.**	**C.**	**U.**	**R.**	**MW.**	**C.**	**U.**	**R.**	**MW.**	**C./Urb**
NOx	551	412	433	882	586	445	414	893	998	907	770	1378	1011	762	904	1376	673	496	659	762	641
NO_2	117	81	97	191	136	103	105	199	191	156	153	281	188	131	165	271	139	88	164	161	113
CO	28	39	23	20	21	33	8	17	106	155	48	106	44	83	46	1	34	78	8	17	103
CO_2	154	156	135	173	156	153	128	181	164	173	145	174	165	156	151	186	158	147	120	169	148
PN $\times 10^{1}$	0.03	0.06	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.04

DV4

	RDE-1				RDE-2				RDE-1-Dyn				RDE-2-Dyn				City-MW				Hill
	C.	**U.**	**R.**	**MW**	**C.**	**U.**	**R.**	**MW**	**C.**	**U.**	**R.**	**MW.**	**C.**	**U.**	**R.**	**MW.**	**C.**	**U.**	**R.**	**MW.**	**C./U.**
NOx	146	122	143	182	147	124	168	156	684	673	749	643	605	661	748	448	179	100	156	230	203
NO_2	42	32	40	56	41	32	47	46	162	146	186	159	152	160	189	117	38	26	37	46	53
CO	5	4	8	4	5	5	6	3	9	11	7	10	3	0	0	9	9	5	1	13	4
CO_2	160	193	132	146	155	179	131	147	174	212	147	155	172	209	139	161	152	170	111	152	173
PN $\times 10^{11}$																					

DV5

	RDE-1				RDE-2				RDE-1-Dyn				RDE-2-Dyn				City-MW				Hill
	C.	**U.**	**R.**	**MW**	**C.**	**U.**	**R.**	**MW**	**C.**	**U.**	**R.**	**MW.**	**C.**	**U.**	**R.**	**MW.**	**C.**	**U.**	**R.**	**MW.**	**C./U.**
NOx	21	22	17	25	44	39	9	79	28	30	22	31	141	130	86	203					59
NO_2	5	5	3	5	8	6	2	15	4	5	3	4	15	14	7	23					16
CO	45	26	93	22	25	29	35	12	20	33	4	21	51	45	115	0					57
CO_2	157	188	131	140	155	189	128	140	170	235	122	139	183	247	145	154					194
PN $\times10^{11}$	0.03	0.03	0.03	0.02	0.3	0.6	0.08	0.07	1.5	3.8	0.3	0.2	-	-	-	-					-

DV6

	RDE-1				RDE-2				RDE-1-Dyn				RDE-2-Dyn				City-MW				Hill
	C.	**U.**	**R.**	**MW**	**C.**	**U.**	**R.**	**MW**	**C.**	**U.**	**R.**	**MW.**	**C.**	**U.**	**R.**	**MW.**	**C.**	**U.**	**R.**	**MW.**	**C./Urb**
NOx	75	89	45	88	81	84	81	77	376	325	367	449	224	256	162	248	141	131	88	173	93
NO_2	21	23	18	22	23	28	22	19	126	107	109	168	82	78	56	111	67	47	40	92	38
CO	26	57	5	6	0	0	0	0	0	0	0	0	60	199	0	0	21	43	11	12	4
CO_2	150	178	127	134	149	175	133	133	156	186	138	139	168	228	120	146	137	163	110	134	197
PN $\times10^{11}$	5.4	8.5	4.4	1.9	4.6	7.6	4.0	1.9	6.1	8.4	5.4	4.0	6.0	13	2.5	1.6	3.4	6.2	3.13	1.8	-

DV7

	RDE-1					RDE-2					RDE-1-Dyn					RDE-2-Dyn					City-MW					Hill
	C.	**U.**	**R.**	**MW**		**C.**	**U.**	**R.**	**MW**		**C.**	**U.**	**R.**	**MW.**		**C.**	**U.**	**R.**	**MW.**		**C.**	**U.**	**R.**	**MW.**		**C./Urb**
NOx	17	30	9	7		9	13	4	9		40	67	23	23		38	75	24	12		13	25	23	6		31
NO_2	0	1	0	0		1	1	1	1		2	5	0	0		2	2	1	1		2	3	3	2		1
CO	40	52	29	36		0	0	0	0		49	65	36	41		4	10	0	0		30	45	27	23		65
CO_2	151	182	120	142		153	178	121	151		152	182	122	145		153	185	122	148		135	147	116	133		162
PN $\times 10^{11}$	0.05	0.09	0.03	0.02		0.06	0.07	0.03	0.07		0.3	0.3	0.3	0.1		0.1	0.2	0.2	0.1		0.3	0.7	1	0.6		0.03

DV8

	RDE-1					RDE-2					RDE-1-Dyn					RDE-2-Dyn					City-MW					Hill
	C.	**U.**	**R.**	**MW**		**C.**	**U.**	**R.**	**MW**		**C.**	**U.**	**R.**	**MW.**		**C.**	**U.**	**R.**	**MW.**		**C.**	**U.**	**R.**	**MW.**		**C./Urb**
NOx	31	35	26	29		89	61	71	138		318	252	267	464		57	101	29	31		19	29	13	15		72
NO_2	4	4	2	6		8	3	7	15		23	15	17	40		4	3	4	4		0	0	0	0		0
CO	0	12	0	0		40	57	22	33		6	6	3	10		55	73	40	47		0	0	0	0		25
CO_2	134	144	113	138		143	155	117	151		159	184	127	162		141	155	112	150		131	126	103	138		140
PN $\times 10^{11}$	0.7	0.7	0.7	0.5		0.6	0.6	0.5	0.5		0.7	1	0.6	0.5		0.7	0.8	0.6	0.5		0.6	0.7	0.6	0.6		0.5

DV9

	RDE-1				RDE-2				RDE-1-Dyn				RDE-2-Dyn				City-MW				Hill
	C.	**U.**	**R.**	**MW**	**C.**	**U.**	**R.**	**MW**	**C.**	**U.**	**R.**	**MW.**	**C.**	**U.**	**R.**	**MW.**	**C.**	**U.**	**R.**	**MW.**	**C./Urb**
NOx	59	70	43	58	54	63	41	57	321	327	318	316	317	382	225	326	34	46	40	26	51
NO_2	17	22	12	15	8	10	6	8	40	39	37	44	39	43	26	45	0	0	0	0	1
CO	8	8	1	15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CO_2	188	221	156	178	188	215	155	187	210	247	171	203	208	259	160	193	171	196	150	160	202
PN $\times 10^{11}$	0.02	0.03	0.02	0.02	0.02	0.03	0.02	0.02	0.06	0.08	0.05	0.05	0.06	0.1	0.04	0.03	<0.01	<0.01	<0.01	<0.01	0.02

DV10

	RDE-1				RDE-2				RDE-1-Dyn				RDE-2-Dyn				City-MW				Hill
	C.	**U.**	**R.**	**MW**	**C.**	**U.**	**R.**	**MW**	**C.**	**U.**	**R.**	**MW.**	**C.**	**U.**	**R.**	**MW.**	**C.**	**U.**	**R.**	**MW.**	**C./Urb**
NOx	92	32	39	242	145	47	47	337	385	316	236	627	290	273	219	376	89	26	67	136	
NO_2	22	7	11	55	31	8	12	71	125	94	88	202	94	74	93	119	16	0	15	30	
CO	47	45	36	64	23	5	11	51	40	42	39	40	8	0	1	35	56	41	20	74	
CO_2	169	199	137	162	169	197	138	162	165	196	134	157	159	186	126	157	151	175	123	142	
PN $\times 10^{11}$	0.03	0.03	0.02	0.02	0.02	0.02	0.01	0.02	0.1	0.2	0.06	0.04	0.04	0.06	0.04	0.03	0.01	0.02	0.01	0.01	

GV1

	RDE-1					RDE-2					RDE-1-Dyn					RDE-2-Dyn					City-MW					Hill
	C.	**U.**	**R.**	**MW**		**C.**	**U.**	**R.**	**MW**		**C.**	**U.**	**R.**	**MW.**		**C.**	**U.**	**R.**	**MW.**		**C.**	**U.**	**R.**	**MW.**		**C./Urb**
NOx	6	8	7	3		6	9	5	2		14	25	10	2		11	18	10	5		9	11	13	5		8
NO_2	0	0	0	0		0	0	0	0		0	0	0	0		0	0	0	0		0	0	0	0		0
CO	699	352	766	1127		662	447	172	1360		1494	645	1927	2249		4163	2484	4581	5709		370	315	264	439		1046
CO_2	158	151	149	179		152	152	127	174		171	179	155	177		162	151	153	183		163	165	120	175		140
PN $\times 10^{11}$	3.9	3.1	4.2	4.8		7.4	6.5	6.1	9.5		11	10	11	12		11	12	10	10		2.6	1.8	2.6	3.0		10

GV2

	RDE-1					RDE-2					RDE-1-Dyn					RDE-2-Dyn					City-MW					Hill
	C.	**U.**	**R.**	**MW**		**C.**	**U.**	**R.**	**MW**		**C.**	**U.**	**R.**	**MW.**		**C.**	**U.**	**R.**	**MW.**		**C.**	**U.**	**R.**	**MW.**		**C./Urb**
NOx	13	20	6	10		16	19	8	20		13	19	10	6		11	16	7	9		11	15	9	9		19
NO_2	2	2	1	2		4	4	3	4		3	3	3	4		3	2	2	3		3	3	3	3		3
CO	3344	149	1011	10910		1039	242	343	2666		6727	3078	4598	14101		5741	1979	3930	11443		2234	145	773	4121		450
CO_2	154	188	119	146		157	186	122	150		155	196	122	135		149	169	123	148		135	156	108	129		166
PN $\times 10^{11}$	2.0	3.9	0.6	0.8							5.4	10	2.6	1.8		3.5	6.7	1.	1.1		1.7	3.9	0.7	0.5		5.1

GV3

	RDE-1					**RDE-2**					**RDE-1-Dyn**					**RDE-2-Dyn**					**City-MW**					**Hill**
	C.	**U.**	**R.**	**MW**		**C.**	**U.**	**R.**	**MW**		**C.**	**U.**	**R.**	**MW.**		**C.**	**U.**	**R.**	**MW.**		**C.**	**U.**	**R.**	**MW.**		**C./Urb**
NOx	38	73	19	7		39	58	50	7		25	41	23	6		41	91	20	6		21	53	7	5		56
NO_2	0	1	0	0		1	1	1	1		0	0	0	0		0	1	0	0		0	0	0	0		3
CO	170	149	202	162		245	223	156	350		1398	382	1831	2255		1057	368	1782	1146		455	185	724	561		167
CO_2	135	166	105	126		123	111	120	139		152	183	127	135		145	156	131	145		137	153	99	134		156
PN $\times 10^{11}$	11	20	51	7.2		12	12	9.4	15		25	46	9.9	14		31	65	11	13		8.9	11	5.0	8.7		19

GV4

	RDE-1					**RDE-2**					**RDE-1-Dyn**					**RDE-2-Dyn**					**City-MW**					**Hill**
	C.	**U.**	**R.**	**MW**		**C.**	**U.**	**R.**	**MW**		**C.**	**U.**	**R.**	**MW.**		**C.**	**U.**	**R.**	**MW.**		**C.**	**U.**	**R.**	**MW.**		**C./Urb**
NOx	98	119	152	11		84	142	91	11		91	189	36	18		95	223	31	11		62	124	112	8		288
NO_2	2	2	2	2		2	2	1	2		3	4	2	3		2	3	2	3		2	3	2	2		2
CO	1022	364	667	2323		958	405	354	2115		1838	1613	1446	2594		3315	3232	2266	4350		930	264	1391	1238		199
CO_2	133	149	117	126		147	165	121	149		165	214	129	140		162	200	131	146		132	149	113	125		167
PN $\times 10^{11}$	22	28	15	22		25	28	16	30		37	56	25	27		31	43	21	28		21	22	14	22		27

GV5

	RDE-1					RDE-2					RDE-1-Dyn					RDE-2-Dyn					City-MW					Hill
	C.	**U.**	**R.**	**MW**		**C.**	**U.**	**R.**	**MW**		**C.***	**U.**	**R.**	**MW.**		**C.**	**U.**	**R.**	**MW.**		**C.**	**U.**	**R.**	**MW.**		**C./Urb**
NOx	13	17	10	12		9	18	2	4		23	44	15	5		17	33	13	3		5	10	3	3		
NO_2	0	0	0	0		1	2	1	1		2	2	1	2		1	2	1	1		1	1	0	1		
CO	257	137	146	561		376	77	113	970		1078	364	752	2425		650	439	301	1200		108	55	56	145		
CO_2	151	184	116	143		157	191	118	149		172	217	136	155		164	208	127	154		140	162	114	134		
PN $\times 10^{11}$	1	0.1	0.8	0.8		0.8	1.2	0.6	0.6		1.3	1.7	1.2	1.1		1.1	1.4	1.0	1.0		1.0	1.3	1.0	0.8		

GV6

	RDE-1					RDE-2					RDE-1-Dyn					RDE-2-Dyn					City-MW					Hill
	C.	**U.**	**R.**	**MW**		**C.**	**U.**	**R.**	**MW**		**C.**	**U.**	**R.**	**MW.**		**C.**	**U.**	**R.**	**MW.**		**C.**	**U.**	**R.**	**MW.**		**C./Urb**
NOx	20	21	5	35		22	48	7	5		16	33	5	4		16	38	2	5							
NO_2	0	0	0	0		0	0	0	0		0	0	0	0		0	0	0	0							
CO	1050	973	524	1739		925	455	569	1764		8601	8245	5237	12837		6501	6309	4580	8472							
CO_2	214	273	173	174		188	217	146	192		222	281	173	197		208	256	161	199							
PN $\times 10^{11}$	18	18	11	25		24	32	16	21		110	130	79	110		97	120	67	98							

GV7

	RDE-1					RDE-2					RDE-1-Dyn					RDE-2-Dyn					City-MW					Hill
	C.	**U.**	**R.**	**MW**		**C.**	**U.**	**R.**	**MW**		**C.**	**U.**	**R.**	**MW.**		**C.**	**U.**	**R.**	**MW.**		**C.**	**U.**	**R.**	**MW.**		**C./Urb**
NOx	60	101	37	27		31	52	13	18		113	195	72	51		70	143	37	21		18	31	50	7		25
NO_2	1	1	1	0		0	0	0	0		4	4	3	5		0	0	0	0		0	0	0	0		0
CO	252	80	102	660		614	76	21	1751		3971	2125	4840	5436		2635	2961	3610	1500		307	102	346	412		127
CO_2	164	206	132	138		167	211	122	147		179	236	133	155		181	253	133	147		154	191	131	137		186
PN $\times10^{11}$	27	33	17	32		34	31	12	54		67	81	54	64		57	89	39	39		18	20	15	17		19

GV8

	RDE-1					RDE-2					RDE-1-Dyn					RDE-2-Dyn					City-MW					Hill
	C.	**U.**	**R.**	**MW**		**C.**	**U.**	**R.**	**MW**		**C.***	**U.**	**R.**	**MW.**		**C.**	**U.**	**R.**	**MW.**		**C.**	**U.**	**R.**	**MW.**		**C./Urb**
NOx	24	34	11	24		15	25	3	14		205	251	314	25		25	32	14	26		16	25	11	12		18
NO_2	2	2	1	1		1	2	1	1		12	16	16	3		2	2	1	2		2	2	1	2		3
CO	189	41	83	520		133	26	17	353		2408	1118	2861	3625		3065	766	2422	6102		181	23	17	294		149
CO_2	173	210	135	162		170	188	135	178		179	214	145	170		189	223	156	183		158	167	132	160		182
PN $\times10^{11}$	0.2	0.2	0.1	0.2		0.2	0.2	0.1	0.2		0.2	0.3	0.2	0.2		0.4	0.4	0.3	0.5		0.1	0.1	0.1	0.2		0.1

*During a second repetition of the same dynamic test the emissions factors for the complete test were: NOx 23mg/km, NO_2 2mg/km, CO 3973mg/km, CO_2 190g/km, PN 5×10^{10} #/km

CNG-LCV

	RDE-1					**RDE-2**					**RDE-1-Dyn**					**RDE-2-Dyn**					**City-MW**					**Hill**
	C.	**U.**	**R.**	**MW**		**C.**	**U.**	**R.**	**MW**		**C.**	**U.**	**R.**	**MW.**		**C.**	**U.**	**R.**	**MW.**		**C.**	**U.**	**R.**	**MW.**		**C./Urb**
NOx	308	641	123	42		354	702	253	47		852	1718	527	89		1060	1673	1052	307		242	659	178	51		515
NO_2	15	23	9	9		15	26	11	7		27	55	13	6		39	63	34	12		16	32	11	9		21
CO	369	270	274	612		245	111	155	478		187	123	119	349		230	195	203	298		440	150	203	635		317
CO_2	256	296	211	249		231	277	181	223		287	342	240	269		277	323	227	267		251	277	206	248		251
PN $\times 10^{11}$	11	26	0.6	0.2		1.6	3.7	0.4	0.3																	

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