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Real Driving Emissions Regulation

European Methodology to fine tune the EU Real Driving Emissions data evaluation method

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Abstract

This European Commission – JRC Technical Report presents a detailed analysis of a dataset made up of 11 passenger cars which have been emission tested during on-road trips for a total of 79 tests. The data set was mostly produced at JRC; except for 3 vehicles. In the framework of the United Nations Economic Commission for Europe (UNECE), the JRC supports DG-GROW (Internal Market, Industry, Entrepreneurship and SMEs) in order to develop an UNECE Regulation and a Global Technical Regulation (GTR) which should include real driving emissions (RDE) testing provisions for several extra-EU countries starting from Japan and Republic of Korea and possibly including India, China, Canada and United States. As a preliminary input to the Global Real Driving informal working group at UNECE, this Report describes the latest EU-RDE procedure (RDE-4, Regulation EU 2018/1832) with focus on the response given by the RDE data analysis tool (EMROAD version 6.03, designed and maintained by JRC). The data set includes RDE tests expressily designed to cover extended boundary conditions (e.g. for temperature and altitude) and to challenge the requirements on trip dynamics which were laid down in the legislation to define the normal condition of vehicle use. EMROAD succesfully produced, and evaluated against requirements, the entire set of parameters defining the trip validity: trip duration, distance and distance shares, vehicle speed and speed shares, trip dynamics, ambient conditions, elevation gain, trip severity with respect to the WLTP driving cycle (based on CO_2), emissions of pollutants and their correction for ambient boundary conditions and for excess of severity. The tool was also used to fine tune the tolerances around the CO_2 characteristic curve, an useful feature when assessing the degree of test severity which is considered acceptable by the legislator in a specific country. In addition, EMROAD incorporates the previous RDE-3 package (Regulation EU 2017/1151) so that a comparison between the old and most recent provisions can be done. For instance, it was found that the data set was affected by the different methods used in RDE-3 and RDE-4 to build the moving averaging windows for the evaluation of overall trip dynamics: more RDE tests are valid with the latest RDE-4 method than with the older RDE-3.

1 Introduction

1.1 Outline and Scope

This European Commission (EC) - Joint Research Centre (JRC) Technical Report presents the results of a study on Real-Driving Emissions (RDE). Considering the recent and rapid development of relevant European Union (EU) legislation on RDE and the importance of worldwide harmonized legislation for the EU vehicles safety, environmental protection and trade, this Report updates the methodology used to optimize the data evaluation according to the latest RDE legislative package ([1]), also referred to as RDE package 4 (or RDE-4, enforcement in 2019) and according to the latest version of the tool for RDE data analysis developed by the EC (see chapter 2.5). This work supports the European Commission contribution in the framework of the World Forum for Harmonization of Vehicle Regulations of the United Nations Economic Commission for Europe (UNECE) ([2]).

Box 1. Scope

This study is based on tests conducted on 11 passenger cars equipped with Portable Emission Measurement Systems (PEMS) and was commissioned by the European Commission - Directorate General Internal Market, Industry, Entrepreneurship and SMEs (DG-GROW). It presents the methodology used to optimize the data evaluation applicable to RDE tests of passenger cars according to the most recent EU legislation (Regulation EU 2018/1832, also known as RDE package-4).

1.2 Rationale

The transport sector and in particular vehicular emissions from internal combustion engines represent a large fraction of pollutants and carbon dioxide emissions in the European Union. The 2018 Report of the European Environmental Agency on Air Quality (EEA, 2018) confirms that air pollution is the single largest environmental health risk in Europe causing around 400 000 premature deaths per year. Road transport is responsible for 39% of nitrogen oxides emissions, 28% of black carbon (particulate matter such as soot), and 20% of carbon monoxide. Particulate matter, nitrogen oxides (and in particular nitrogen dioxide) and ground-level ozone are the pollutants that most affect human health due to a combination of toxicity and exposure.

Since 1970 road vehicles introduced in the EU market are subject to a type-approval procedure which includes emission testing and compliance with legislative emission limits. From the introduction of the Euro 1 standard in 1992 the procedure became progressively more detailed and limits more stringent along with rapid technological development of anti-pollution systems such as those treating vehicles exhaust. At present, the active environmental standard for passenger cars is the Euro 6 valid from 2014 (Regulation EU 715/2007 and Regulation EU 692/2008). In Type 1 Test of EU type-approval (i.e., “Verifying average exhaust emissions at ambient conditions”) a vehicle follows a prescribed speed trace and its tailpipe emissions are characterized in terms of total hydrocarbons (THC), carbon monoxide (CO), nitrogen oxides (NOx), particulate mass (PM) and particle number (PN). The emission factors calculated in mass/distance units have to comply with limit values reported in Table 1.

As a consequence, road transport decreased its share of emissions since 1990. However, the continuous growth of the EU fleet and in particular the increasing fraction of diesel vehicles (traditionally associated with larger NOx and PM emissions than gasoline) reduced the potential for air quality improvement. Note that recent studies confirmed the critical aspects related to old diesel vehicles (Euro 0 to Euro 3), but mitigate the impact of modern diesel compared to modern gasoline vehicles (Platt et al., 2014, and

([1]) Regulation (EU) 2018/1832, Official Journal L 301, 27.11.2018, p. 1–314. Available at: https://eur-lex.europa.eu/.

([2]) https://www.unece.org/trans/main/wp29/meeting_docs_grpe.html references therein), at least for what concerns particulate matter. In addition, discrepancies between expected and real pollution reduction had also increased due to emission gaps between vehicles tested in the laboratory and driven on the road.

Table 1. Euro 6 limit values for test Type 1 of the type-approval procedure: tailpipe emissions.

Technology	CO mg/km	HC mg/km	HC+NOx mg/km	NOx mg/km	PM mg/km	PN #/km
Compressed ignition	1000	–	170	80	5 (3)	6.0×10^{11}
Spark-ignition	1000	100 (1)	–	60	5 (2)(3)	6.0×10^{11} (3)(4)

(1) Non-Methane hydrocarbons limit = 68 mg/km
(2) Applicable only to vehicles using DI engines
(3) 4.5 mg/km using the PMP measurement procedure ([3])
(4) 6.0×10^{12} #/km within first three years from Euro 6 effective dates

Source: Regulation EU 2017/1151.

1.3 Real driving emissions

Emissions produced on-road, with varying rolling resistance and aerodynamic drag, free gear-shift strategy and driving style, non-zero positive altitude gain, and uncontrolled ambient conditions are expected to vary, in comparison to those produced in a controlled laboratory experiment following a prescribed speed trace. JRC started in 2007 a series of experimental activities with the scope of investigating real-world emissions using on-board instrumentation such as PEMS. Specifically for light-duty vehicles (i.e., passenger cars) large discrepancies between laboratory and on-road were found for NOx emitted by diesel passenger cars (Weiss et al., 2013). These findings and other elements triggered regulatory efforts: The EU adopted in 2016 a first RDE package (Regulation EU 2016/427) which defined procedures, instrumentation requirements and evaluation method. Since then RDE was subject to 3 major legislation revisions. A non-exhaustive chronology of EU-RDE legislation is presented in Table 2 which includes the relevant JRC Reports. At present, the 4th package of RDE legislation (Regulation EU 2018/1832) is active and applicable for vehicles Euro 6d-TEMP starting from January 2019 Comprehensive treatment of technical aspects and procedures related to the use of PEMS in RDE tests can be found in the JRC Report by Valverde et al. (2018).

1.4 JRC role in the Global RDE group (UNECE)

The Sustainable Transport Unit (STU) of the Directorate for Energy, Transport and Climate at the European Commission – Joint Research Centre routinely supports the activity of United Nations Economic Commission for Europe (UNECE), World Forum for Harmonization of Vehicle Regulations (WP.29) upon requests from customers Directorate General (DG-GROW, in this case). At present, UNECE Regulation No. 83 and Global Technical Regulation (GTR) No. 15 ([4]) contain uniform provisions concerning the approval of vehicles with regard to the emission of pollutants according to engine and/or fuel requirements. However, none of these UNECE Regulations currently include provisions for checking the real driving emissions of pollutants. In 2018 the European Commission (EC) together with Japan and the Republic of Korea requested the authorization to develop a new GTR and UNECE Regulation on RDE with the scope of "*Developing a methodology for determining the real driving emissions of light duty vehicles based on globally harmonized traffic conditions and boundaries*". For this purpose an informal working

([3]) See https://wiki.unece.org/pages/viewpage.action?pageId=2523173
([4]) Available at https://www.unece.org/trans/main/wp29/wp29regs81-100.html and at https://www.unece.org/trans/main/wp29/wp29wgs/wp29gen/wp29glob_registry.html

group (IWG) named "Global RDE" ([5]) was established and the following tasks assigned: Create, review and finalize a draft UNECE GTR and UNECE Regulation on RDE. The initially proposed timeline envisaged a draft GTR submission to UNECE by mid-2019 and finalization by the end of 2019. Given the high level of expertise on RDE acquired by EU in the last decade, and considering that other Contracting Parties have developed or plan to develop RDE tests, the IWG intend to use the work already performed and experience gained in the development of the EU-RDE procedure. The JRC supports DG-GROW in the UNECE framework, and specifically on this topic the task is formalized in the Administrative Arrangement N ° SI2.784345 - JRC.35074.

Table 2. Basic chronology of EU-RDE legislation and related JRC research publications.

Year	Euro	EU-RDE	JRC Report	EU-legislation (1)
2005	Euro 4	Pre-RDE activity		
2007	Euro 4	Pre-RDE activity		715/2007 692/2008
2011-2013	Euro 5b	RDE-HDV(2)	JRC 66031 JRC 62639 JRC 75998	582/2011
2014	Euro 6			
2015			JRC 93743 JRC 97357	
2016	Euro 6a,b	RDE 1 RDE 2		2016/427 2016/646
2017	Euro 6c	RDE 3	JRC 105595	2017/1151 2017/1154
2019	Euro 6d-temp	RDE 4	JRC 109812	2018/1832

(1) Available at: https://eur-lex.europa.eu/
(2) Heavy-duty Vehicle

Source: JRC.

([5]) Description and working documents, including draft GTR are public and available at: https://wiki.unece.org

2 Experiments and method

2.1 JRC dataset for the Global RDE group

This JRC Report is based on a dataset of 79 RDE tests on 11 vehicles (10 passenger cars and 1 light commercial vehicle) carried out mainly by JRC (vehicles 1 to 9, see paragraph 2.3) or provided to JRC by research/contracting partners (vehicles 9, 10 and 11). The fleet is a mix of petrol, diesel and hybrid vehicles, type-approved mainly under the Euro 6b and Euro 6 standards; see Table 3.

The on-road tests were preceded by roller bench tests in order to quality-check the vehicle and the PEMS instrumentation and additionally to determine the WLTC CO_2 reference mass used in the post-processing of the data. The JRC dataset consists of:

— A series of WLTC ([6]) emission tests performed on the roller bench (see section 2.3)

— An input RDE dataset consisting of 79 RDE tests on 11 vehicles equipped with PEMS

— An output RDE dataset as a result of the processed input by the EMROAD tool version 6.03, which is in line with the provisions laid down in Regulation EU 2018/1832, i.e. RDE package number 4; see section 2.5.

Figure 1 summarizes the number of RDE tests per vehicle with color-coded fuel type and annotated model of the PEMS installed on-board of the vehicles.

Table 3. JRC dataset at a glance.

Parameter		# of Vehicles
Vehicles		11
Category	M1	10
	N1	1
Euro	Euro 5	1
	Euro 6	4
	Euro 6b	6
Petrol		4
Diesel		6
Hybrid		1
Total No. of tests		79
Route types		8

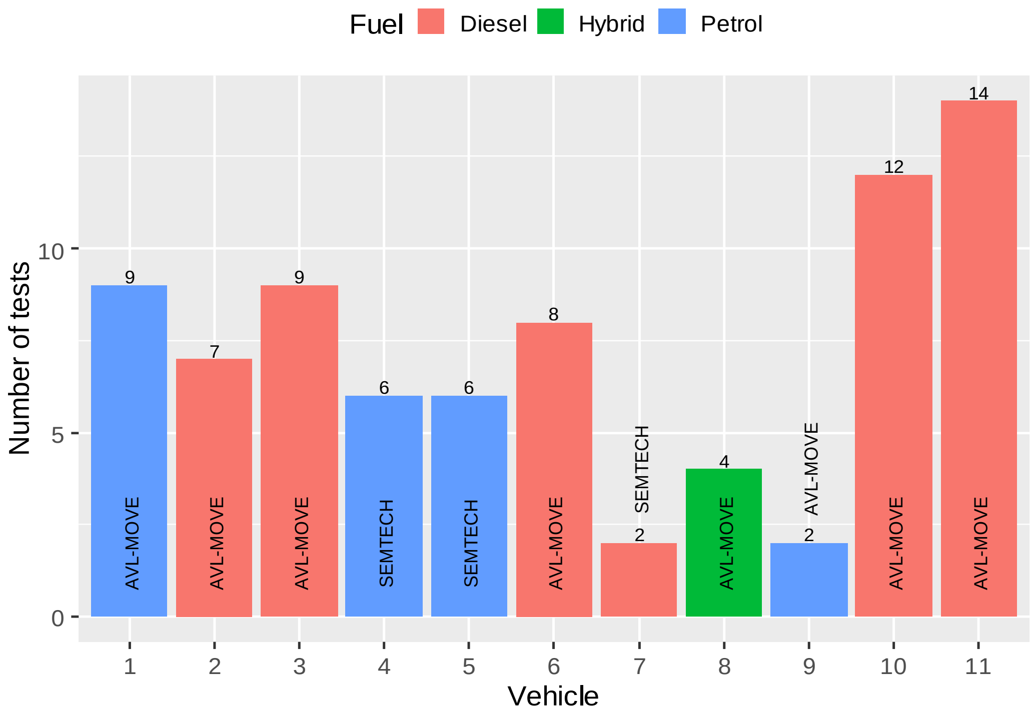
Source: JRC.

2.2 Test facility

The Vehicle Emissions Laboratory (VELA) of the European Commission − Joint Research Centre (Italy) has been described e.g. in Clairotte et al. (2017). Here briefly, the dynamometer test cell suitable for passenger cars and small commercial vehicles is equipped with two 48'' rolls with inertia range 454-4540 kg (AIP), a Constant Volume Sampler (CVS, flow rate range of 3−30 m^3/min) and integrated gas analyzers (Horiba MEXA-7100, and MEXA-7400 for raw and diluted exhaust, respectively).

([6]) Worldwide-harmonized Light-duty Test Cycle (Regulation EU 2017/1151).

Figure 1. Number of RDE tests per vehicle color-coded by engine type (hybrid = gasoline + electric). PEMS model is annotated.



Source: JRC.

During the WLTC several parameters were acquired at a sampling rate of 10 Hz, then averaged at 1 Hz.

— Raw and diluted instantaneous exhaust concentrations of gaseous components:
  - Flame ionization detector (FID) for THC and methane (CH_4),
  - Chemi-luminescence (CLD) detector for NOx,
  - Non-dispersive infrared (NDIR) for CO and CO_2,
  - Temperatures (thermocouples): Engine oil/coolant, post-catalyst, exhaust,

— Electronic Control Unit (ECU) / On board diagnostic (OBD) signals, such as engine speed, temperatures, etc.

An example of relevant parameters such as actual and scheduled vehicle speed, temperature sensors (oil, precat and postcat) and raw exhaust chemical concentrations produced during a WLTC can be found in Figure 2. The raw exhaust was diluted by a critical flow Venturi and sampled in Tedlar bags for analysis according to Regulation EU 2017/1151 (Type 1 test) for the following purposes:

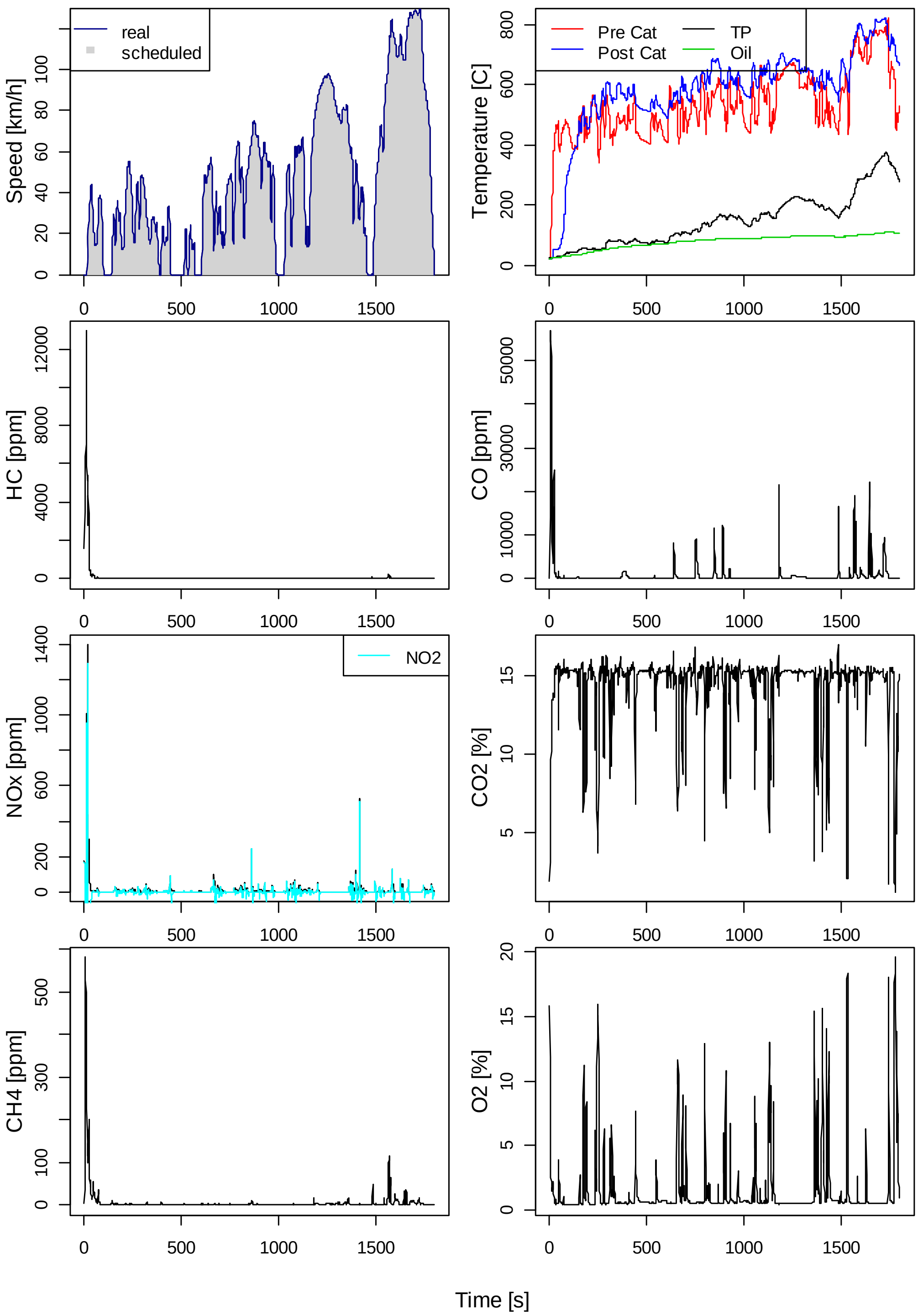
— Confirm the environmental performance of the vehicle

— Determination of WLTP CO_2 emissions from which to determine the CO_2 WLTP reference mass ($M_{CO_{2,ref}}$, expressed in kg) as half of the total CO_2 mass emitted during the test; see section 2.5.

Box 2. Disclaimer

As these vehicles were approved using the NEDC and prior to the introduction of the WLTP, the WLTP tests were not meant to check the vehicle compliance, but to obtain the CO_2 emissions required for the RDE data evaluation. In addition, the WLTP tests ensured that abnormally large emissions did not occur (due to tampering, malfunctioning, etc..).

Figure 2. Speed profile, temperature sensors, and raw exhaust concentrations measured from Vehicle 1 during a WLTC cold start test.



Source: JRC.

2.3 Vehicles and driving cycle

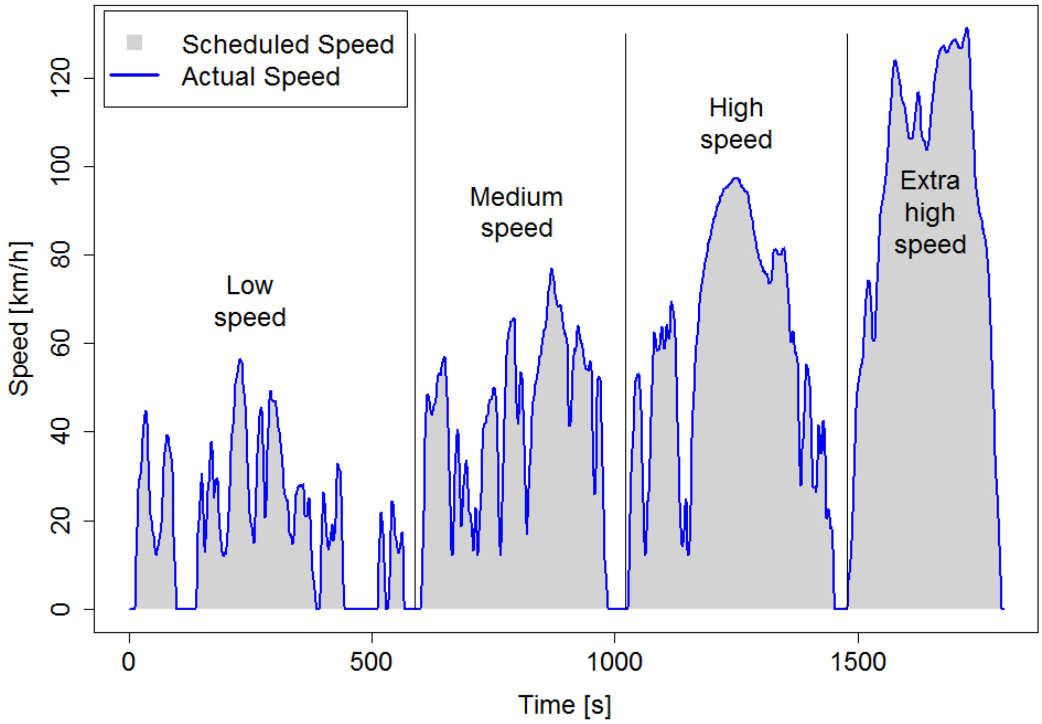
The 10 passenger cars (category M1) and 1 light commercial vehicle (category N1) included in the JRC dataset provided to the RDE-IWG were rented from external companies without the involvement of the vehicle manufacturers except for vehicle 9 (provided by OEM on a volunteer basis). Vehicles from 1 to 8 were tested in the VELA laboratories of JRC, vehicle 9 in the OEM facility, while vehicles 10 and 11 were tested by the Technical University of Graz (TUG, Austria). Basic technical specifications of the test fleet which includes a mix of fuels and after-treatment technologies are given in Table 4. The vehicles were equipped with compressed ignition (6 vehicles), spark ignition (4 vehicles) and hybrid spark-ignition/electric (1 vehicle) engines and were all type-approved according to the EU legislation. Gasoline vehicles featured a three-way catalyst (TWC) for hydrocarbons (HC), carbon monoxide (CO) and nitrogen oxides (NOx) reduction, while diesel vehicles after-treatment consisted of a diesel oxidation catalyst (DOC) and diesel particle filter (DPF) in addition to either a Lean-NOx Trap (LNT) or Selective Catalyst Reduction (SCR) for NOx reduction. All vehicles were emission tested over the WLTC according to Regulation EU 2017/1151; see speed trace in Figure 3. The WLTC is an emission test cycle mandatory for the type-approval of new (since 2017) and existing vehicle types (since 2018) in EU. It consists of 4 phases with increasing average speed called Low, Medium, High and Extra high and is prescribed principally for Type 1 test: Verifying average exhaust emissions at ambient conditions. The WLTC replaces the former New European Driving Cycle (NEDC) which was applicable prior to the entry into force of Regulation EU 2017/1151. For sake of consistency and in agreement with all contracting parties, all vehicles were tested over the WLTC, regardless of their environmental standard. Moreover, the on-road trips have been evaluated in this Report against the latest EU-RDE legislation (RDE-4, not applicable at type-approval of the present test vehicles) which is based on the WLTC in order to determine CO_2 emissions, CO_2 reference mass, and CO_2 characteristic curve according to Regulation EU 2018/1832; see section 2.5.

Box 3. Disclaimer

Vehicles in this Report are not necessarily complying with RDE or WLTC requirements laid down in Regulation EU 2018/1832 and Regulation EU 2017/1151, respectively, as they have been type-approved before enforcement of the above mention legislation.

Figure 4 shows the CO_2 emissions obtained on the roller bench over WLTC tests broken down by driving cycle phase and vehicle (panels). The entire process of RDE evaluation is based on splitting the test data in subsets (windows) according to the **reference CO_2 mass** ($M_{CO2,ref}$) defined as the half of the CO_2 mass emitted by the vehicle over the WLTC test and which determines the length of the windows as per Appendix 5 of Regulation EU 2018/1832. The CO_2 emissions in the low, high and extra-high part of WLTC together with the phase average speeds represent the points P1, P2, P3 used to build the CO_2 characteristic curve described in 4.1.

Figure 3. Speed trace of the Worldwide-harmonized Light-duty Test Cycle (WLTC) followed by a test vehicle on the roller bench.



Source: JRC.

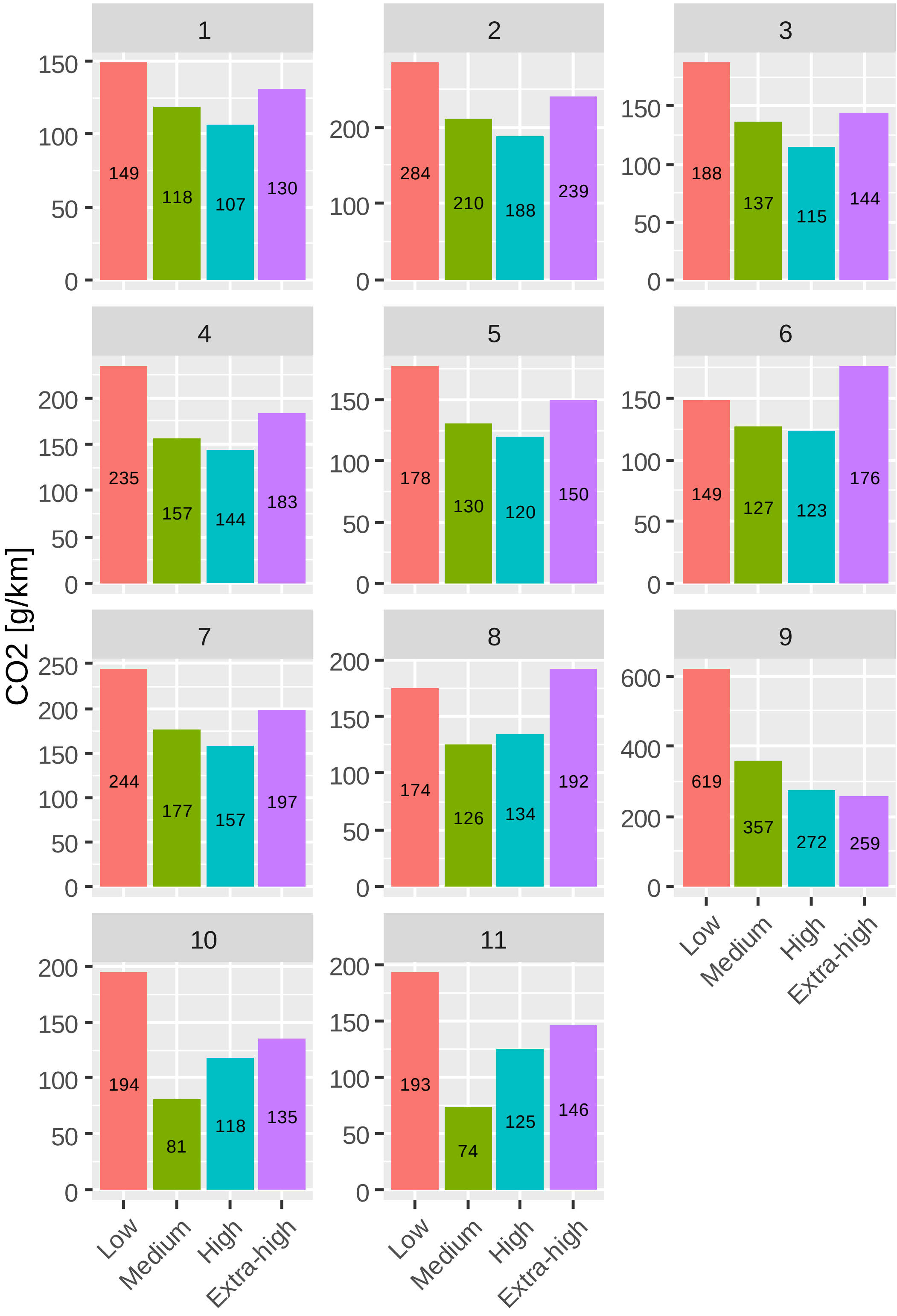
Table 4. Vehicles' technical specifications.

Vehicle	1	2	3	4	5	6	7	8	9	10	11
Category	M1	M1	M1	M1	M1	N1	M1	M1	M1	M1	M1
Engine(1)	SI	CI	CI	SI	SI	CI	CI	SI/Elect.	SI	CI	CI
Displacement [cm³]	999	2967	1968	1618	1242	1560	1968	1395	6750	1968	1968
After-treatment(2)	TWC	DOC,DPF, SCR	DOC,DPF, EGR,LNT	TWC	TWC	DOC,DPF, EGR,SCR	DOC,DPF, EGR	TWC	TWC	DOC,DPF, SCR	DOC,DPF, SCR
EURO	6b	6b	6b	6	6b	6b	5b	6b	6	6	6
Power [kW]	70	193	110	140	51	73	130	110+75	420	140	90
Transmission(5)	MT	AT	AT	AT	MT	MT	AT	AT	AT	AT	MT
Mileage [km]	2539	6479	25602	19934	2336	7900	29173	8395	70000	17000	1700
Mass [kg](4)	1135	2185	1394	1584	940	1309	1678	1524	2600	1607	1598
Year	2016	2017	2017	2013	2016	2017	2013	2015	2015	2016	2017

(1) SI = spark-ignition; CI = compressed ignition
(2) TWC = Three-Way Catalyst; DOC = Diesel Oxidation Catalyst; EGR = exhaust gas recirculation; LNT = Lean NOx Trap; DPF = Diesel Particle Filter; SCR = Selective Catalytic Reduction
(4) Dry mass as per certificate of registration
(5) MT/AT = manual/automatic transmission

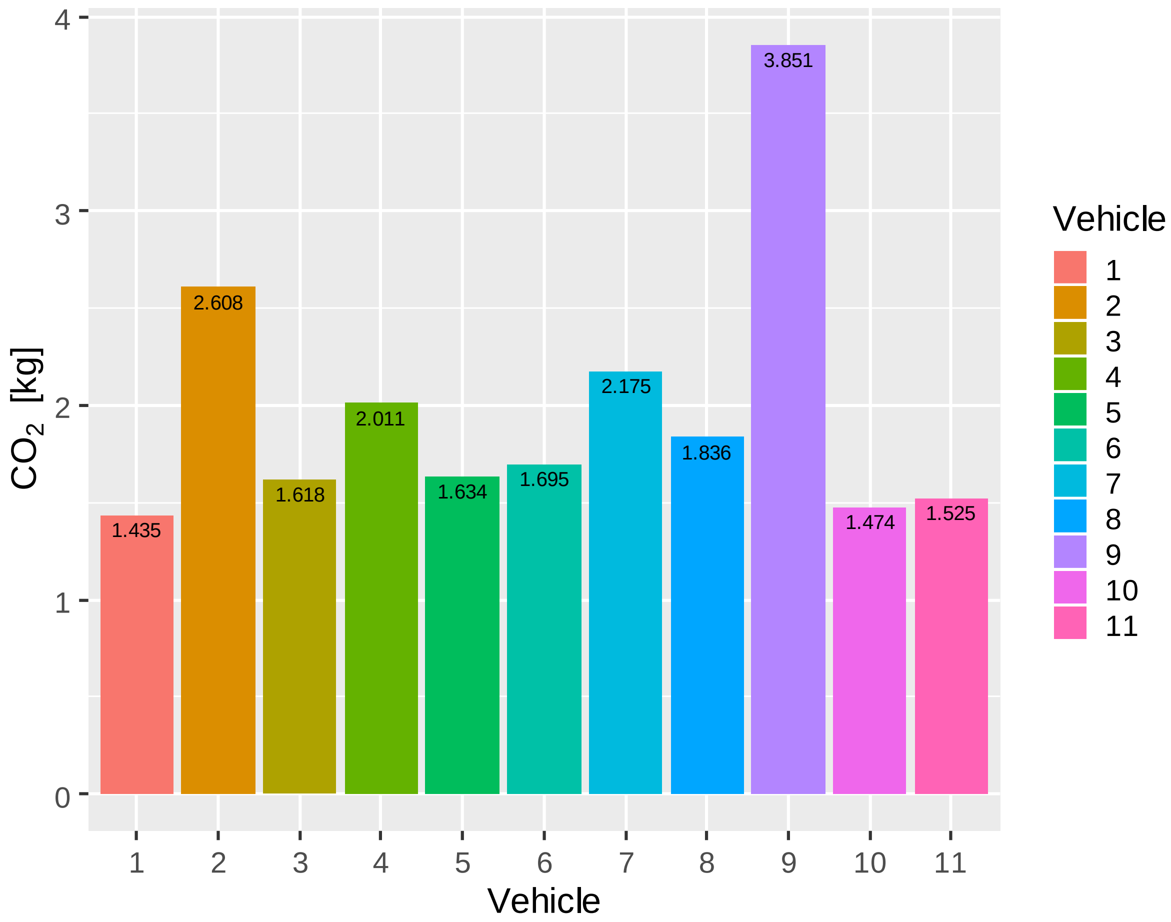
Source: JRC.

Figure 4. Emissions of CO_2 per vehicle (panels) and colour coded by WLTC driving cycle phase: low, medium, high and extra-high speed phases. The low, high and extra-high CO_2 are the points P1, P2 and P3 used to build the CO_2 characteristic curve as explained in 4.1.



Source: JRC.

Figure 5. WLTP reference CO_2 mass ($M_{CO2,ref}$) used for the definition of the CO_2 mass based averaging windows (moving averaging window method, MAW).



Source: JRC.

2.4 On-road tests with PEMS

After being tested over the WLTC, vehicles were equipped with PEMS (see Figure 6) and tested over on-road trips in order to evaluate their real-driving emissions (RDE). We followed the procedures for EU-RDE testing summarized in the JRC Report by Valverde et al. (2018) which provides guidance for the preparation, execution and data quality check of emissions tests with PEMS on board of light-duty vehicles according to the following EU legislation: Regulation EU 2016/427 and Regulation EU 2016/646 (RDE package number 1 and 2), Regulation EU 2017/1151 and Regulation EU 2017/1154 (RDE package number 3) Regulation EU 2018/1832 (RDE package number 4). The number of RDE tests per vehicle (color-coded fuel type) with annotated PEMS instrument was shown in Figure 1.

During RDE tests, the vehicles were equipped with the PEMS modules described in Table 5:

— Gas analysers

— Exhaust flow meter measuring the exhaust mass flow rate at the tailpipe

— Global Navigation Satellite System (GNSS) for vehicle positioning and speed

— Meteorological station for the acquisition of ambient parameters such as air temperature, pressure and relative humidity

— ECU/OBD scan tools for the acquisition of vehicle parameters such as vehicle and engine speed, temperature of oil/coolant.

Individual modules have to fulfil the technical specifications given in the EU relevant legislation in order to be considered RDE compliant.
Figure 7 and Figure 8 show an example of raw PEMS data after an RDE test lasting approximately 100 min. Relevant RDE parameters needed for data post-processing with the EMROAD tool (see section 2.5) were acquired:

— Vehicle position (longitude, latitude, altitude, speed)

— Ambient conditions (air temperature, pressure and relative humidity)

— Vehicle parameters (coolant/oil temperature, engine speed, exhaust temperature)

— Exhaust mass flow

— Tailpipe concentrations (typically of NOx, CO, CO_2, and O_2)

The JRC dataset made of the 79 on-road tests performed with PEMS instrumentation is summarized in Table 6. Each test is associated to a driving intention such as Normal or Dynamics, meaning that at test start the driver was instructed to use typical driving style or a more aggressive one, respectively. Those are indications and may not be reflected in the final results.

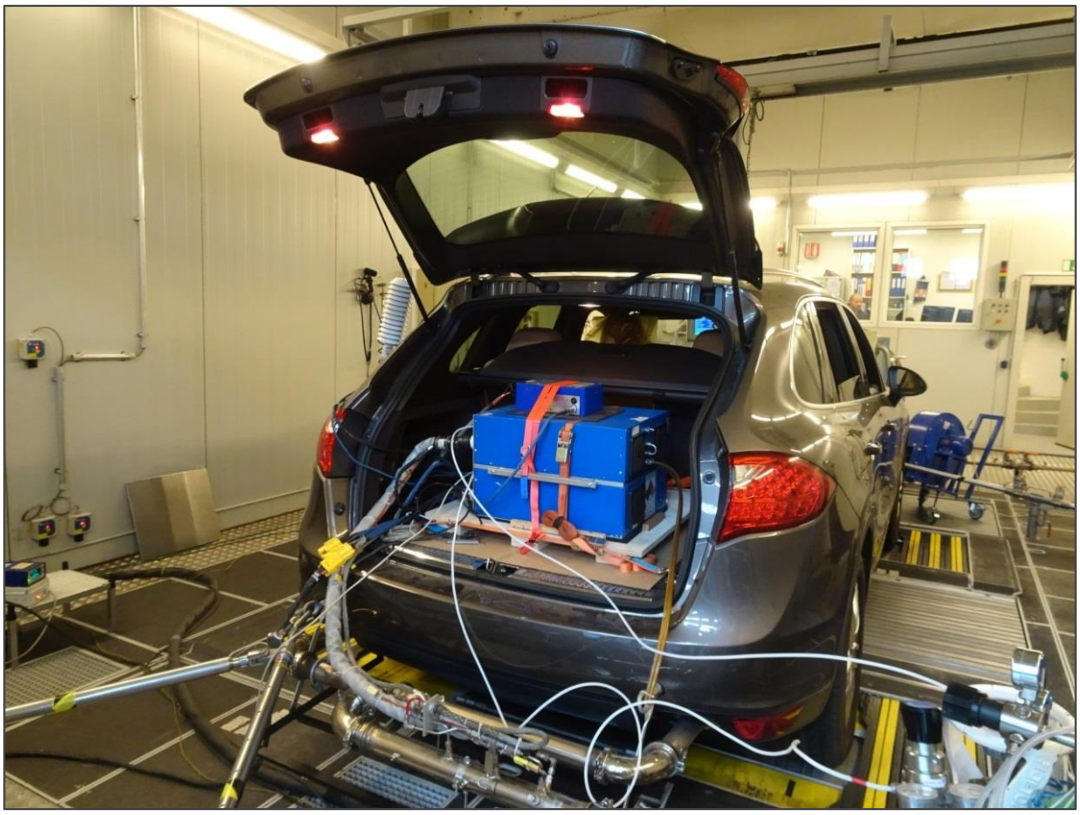
The PEMS dataset was finally fed to the EMROAD software tool (see section 2.5) in order to interpret relevant RDE parameters and determine trip validity.

Table 5. Components of the PEMS setup. The reading of the ECU/OBD is allowed but not mandatory as per Regulation EU 2018/1832. GA = gas analyzer, DC = diffusion charger, DP = differential pressure. NDIR = non-dispersive infrared, NDUV = non-dispersive ultra-violet.

Instrument	Model	Parameter (max range)	Principle	Mandatory
GA	MOVE iS (AVL)	CO (5%), CO_2 (20%)	NDIR	Yes
		NO (5000 ppm), NO_2 (2500 ppm), Sample flow (3.5 l/min, constant),	NDUV	Yes
EFM	MOVE (AVL)	Mass flow rate	DP	Yes
GA+ EFM	SEMTECH DS+	CO (8%), CO_2 (18)%, Sample flow (3 l/min, constant),	NDIR	Yes
		NO (3000 ppm), NO_2 (1000 ppm),	NDUV	
GNSS		Latitude, Longitude, Speed, Altitude,	Satellite	Yes
Meteo station		Ambient temperature, pressure, humidity	Sensors	Yes
OBD		Vehicle speed, Engine speed, coolant/oil T		No

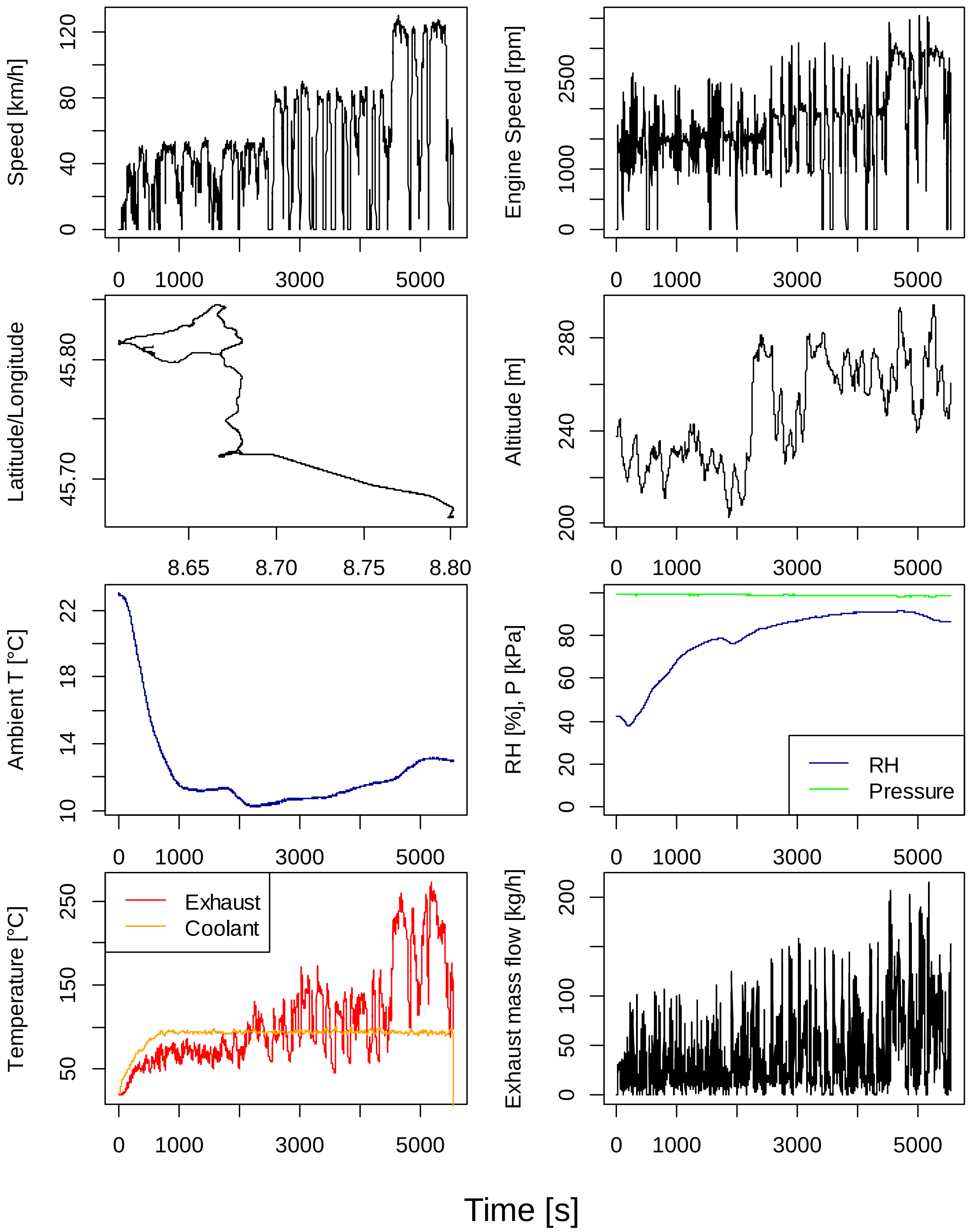
Source: JRC.

Figure 6. Indoor view of the VELA test cell for passenger cars including a vehicle equipped with PEMS.



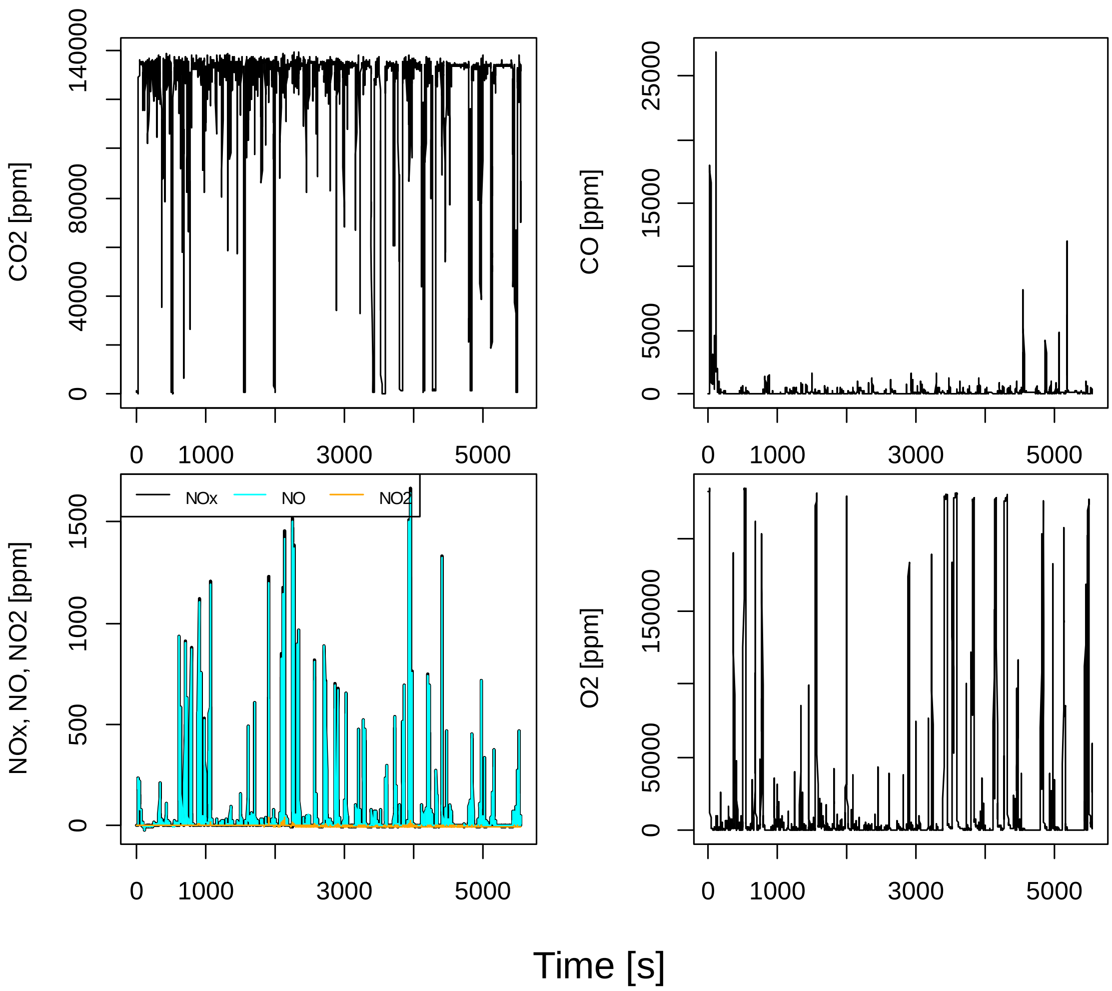
Source: JRC.

Figure 7. Example of PEMS raw data after RDE test 1 of Vehicle 1. Horizontal axis represents time except for the Latitude/Longitude panel.



Source: JRC.

Figure 8. Example of tailpipe concentrations of the chemical species analyzed by the PEMS during RDE test 1 of Vehicle 1.



Source: JRC.

Table 6. List of RDE tests performed on the 11 vehicles equipped with PEMS.

Test No.	Vehicle	Fuel	Driving intention(1)	PEMS Model
1	1	Petrol	Dynamic	AVL-MOVE
2	1	Petrol	Dynamic	AVL-MOVE
3	1	Petrol	Normal	AVL-MOVE
4	1	Petrol	Normal	AVL-MOVE
5	1	Petrol	Normal	AVL-MOVE
6	1	Petrol	Normal	AVL-MOVE
7	1	Petrol	Normal	AVL-MOVE
8	1	Petrol	Normal	AVL-MOVE
9	1	Petrol	Dynamic	AVL-MOVE
10	2	Diesel	Dynamic	AVL-MOVE
11	2	Diesel	Dynamic	AVL-MOVE
12	2	Diesel	Normal	AVL-MOVE
13	2	Diesel	Normal	AVL-MOVE
14	2	Diesel	Normal	AVL-MOVE
15	2	Diesel	Normal	AVL-MOVE
16	2	Diesel	Dynamic	AVL-MOVE
17	3	Diesel	Normal	AVL-MOVE
18	3	Diesel	Normal	AVL-MOVE
19	3	Diesel	Dynamic	AVL-MOVE
20	3	Diesel	Normal	AVL-MOVE
21	3	Diesel	Normal	AVL-MOVE
22	3	Diesel	Normal	AVL-MOVE
23	3	Diesel	Normal	AVL-MOVE
24	3	Diesel	Normal	AVL-MOVE
25	3	Diesel	Dynamic	AVL-MOVE
26	4	Petrol	Normal	SEMTECH
27	4	Petrol	Normal	SEMTECH
28	4	Petrol	Normal	SEMTECH
29	4	Petrol	Normal	SEMTECH
30	4	Petrol	Normal	SEMTECH
31	4	Petrol	Normal	SEMTECH
32	5	Petrol	Dynamic	SEMTECH
33	5	Petrol	Normal	SEMTECH
34	5	Petrol	Normal	SEMTECH
35	5	Petrol	Normal	SEMTECH
36	5	Petrol	Normal	SEMTECH
37	5	Petrol	Dynamic	SEMTECH
38	6	Diesel	Dynamic	AVL-MOVE
39	6	Diesel	Normal Loaded(2)	AVL-MOVE
40	6	Diesel	Normal	AVL-MOVE
41	6	Diesel	Normal	AVL-MOVE
42	6	Diesel	Normal	AVL-MOVE
43	6	Diesel	Normal	AVL-MOVE

44	6	Diesel	Dynamic	AVL-MOVE
45	6	Diesel	Normal – Loaded(3)	AVL-MOVE
46	7	Diesel	Normal	SEMTECH
47	7	Diesel	Normal	SEMTECH
48	8	Hybrid	Normal - Hybrid mode	AVL-MOVE
49	8	Hybrid	Normal - Emode	AVL-MOVE
50	8	Hybrid	Normal - Emode	AVL-MOVE
51	8	Hybrid	Normal - Battery charge mode	AVL-MOVE
52	9	Petrol	Normal	AVL-MOVE
53	9	Petrol	Normal	AVL-MOVE
54	10	Diesel	Normal	AVL-MOVE
55	10	Diesel	Normal	AVL-MOVE
56	10	Diesel	Normal	AVL-MOVE
57	10	Diesel	Normal	AVL-MOVE
58	10	Diesel	Dynamic	AVL-MOVE
59	10	Diesel	Low emissions driving	AVL-MOVE
60	10	Diesel	Normal	AVL-MOVE
61	10	Diesel	Normal	AVL-MOVE
62	10	Diesel	Dynamic	AVL-MOVE
63	10	Diesel	Emissions Provoking Driving	AVL-MOVE
64	10	Diesel	Emissions Provoking Driving Loaded(4)	AVL-MOVE
65	10	Diesel	Emissions Provoking Driving Loaded(5)	AVL-MOVE
66	11	Diesel	Normal	AVL-MOVE
67	11	Diesel	Normal	AVL-MOVE
68	11	Diesel	Normal	AVL-MOVE
69	11	Diesel	Normal	AVL-MOVE
70	11	Diesel	Normal	AVL-MOVE
71	11	Diesel	Normal	AVL-MOVE
72	11	Diesel	Normal	AVL-MOVE
73	11	Diesel	Dynamic	AVL-MOVE
74	11	Diesel	Dynamic	AVL-MOVE
75	11	Diesel	Emissions Provoking Driving Loaded	AVL-MOVE
76	11	Diesel	Emissions Provoking Driving Loaded	AVL-MOVE
77	11	Diesel	Emissions Provoking Driving Loaded	AVL-MOVE
78	11	Diesel	Emissions Provoking Driving Loaded(6)	AVL-MOVE
79	11	Diesel	Emissions Provoking Driving Loaded(7)	AVL-MOVE

(1) The driving intention is an "a priori" decision, not necessarily reflected in the final results.
(2)(3) Loaded = additional 250 kg.
(4)(5) Loaded = additional 175 kg.
(6)(7) Loaded = additional 170 kg.

Source: JRC.

2.5 EMROAD tool

EMROAD ([7]) is a Microsoft Excel add-in for the analysis of vehicle emissions data recorded with PEMS. In the frame of the European legislative PEMS programs for heavy-duty vehicles (HDV), non-road mobile machinery (NRMM), and light-duty vehicles (LDV), EMROAD was developed as a research tool, primarily used to support the development of PEMS data evaluation methods for emissions legislation.

These legislative developments being completed, EMROAD was updated by the JRC to meet:

- For light-duty vehicles, the applicable methods and requirements laid down in Regulations EU 2016/427, 2016/646, 2017/1147 and 2018/1832.
- For heavy-duty vehicles, the applicable methods and requirements laid down in Regulation EU 582/2011 and amendments.
- For non-road mobile machinery, the applicable methods and requirements laid down in Regulation EU 2017/655.

The most important elements checked by EMROAD and considered in this study are:

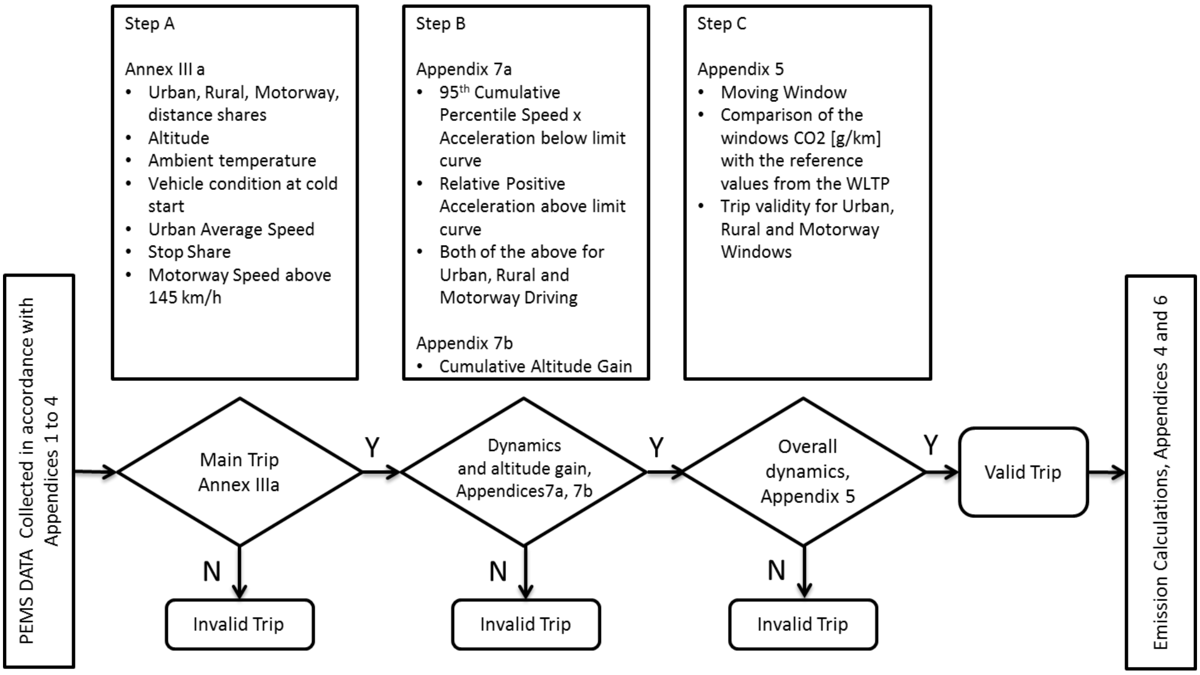
- Trip characteristics such as trip duration, mileage, altitude, vehicle speed and average speed, cumulative elevation gain, ambient temperature and RH
- Excess or absence of driving dynamics
- The overall dynamics using the Moving Averaging Window method (MAW), conducted in accordance with Appendix 5 of Regulation EU 2018/1832, with the exception of the boundaries (tolerances around the CO_2 characteristic values, which were optimised according to the findings presented in this study)
- Emission correction due to the presence of data in extended conditions of ambient temperature and altitude
- Emission correction based on CO_2
- Final real-driving emissions

EMROAD uses "raw" PEMS data as input, calculates according to the sequence illustrated in Figure 9, reports relevant quantities, and checks them against the legislative requirements.

In its version 6.03, EMROAD has been updated to verify test validity and to calculate the final RDE emissions according to the latest EU-RDE provisions. In addition, some of the results presented in this Report highlight the improvements introduced after an optimisation process and with respect to the previous EU-RDE legislative package (known as RDE-3) which is reproducible by selection of appropriate settings in EMROAD 6.03.

([7]) Latest version available at: https://circabc.europa.eu

Figure 9. Diagram of EMROAD calculation steps and related legislation requirements. Adapted from Regulation EU 2018/1832.



Source: JRC.

3 Characteristics of on-road tests

PEMS data acquired during on-road tests were elaborated by the EMROAD tool version 6.03; see section 2.5. The dataset consists of successful tests, i.e., tests performed without severe failures of the vehicle and/or of the PEMS hardware and software including the instrument drift. The validity of successful tests under the RDE-4 package is related to several requirements detailed in chapter 5. Here, the main characteristics of the dataset are outlined.

First of all, general parameters describing the test conditions were extracted from raw PEMS data:

- Test duration
- Test distance
- Vehicle speed
- Speed and distance shares
- Ambient temperature
- Altitude above sea level

Figure 10 displays the total trip duration with the required time range between 90 and 120 minutes (dashed lines). All tests are in the range except for two of them, which are slightly above and below the allowed duration. The cold start duration should last at minimum 5 minutes or until the coolant temperature equals 70 °C, in case of trips started in cold engine conditions; no requirement for trips started in hot engine conditions. In our dataset, the duration below 5 minutes means that the condition on the coolant was met before 5 minutes, while zero duration means that the cold start was not a requirement. Each trip shall cover a distance of minimum 16 km per each driving mode: urban, rural, motorway (no requirement on total distance). In Figure 11 the covered distance is plotted per each trip (upper panel) along with distance shares and allowed ranges (lower panel) according to Table 8. All vehicles were driven for about 100 minutes covering at least 75 km, with only one test of vehicle 10 exceeding the urban distance share.

Figure 12 shows the range of ambient temperature and altitude of the tests: average, minimum and maximum values are reported. Tests were mainly conducted in spring and summer seasons covering a temperature range between about +6 °C and +38 °C and an altitude range between 200 m and 1000 m. According to Regulation EU 2018/1832, PEMS second-by-second data are considered in **extended conditions** when:

- Ambient temperature is between -7 °C and 0 °C or between 30°C and 35°C.

Or/and when:

- Altitude is between 700 m and 1300 m above sea level.

Conditions between 0 °C and 30°C and below 700 m are considered **moderate**, while conditions outside boundaries, i.e. temperature below -7 °C or above 35 °C, or altitude above 1300 m should be excluded from the analysis. At present, data outside the temperature and altitude boundaries (which could be called "extreme" conditions) invalidate an RDE test with PEMS when their amount is above 1%. Clearly from Figure 12, there were PEMS data in extended conditions: their percentage is displayed in Figure 13 with respect to temperature and altitude. Several tests contained data in extended conditions of temperature with 3 tests completely contained. Concerning altitude, only vehicle 10 and 11 overshot the threshold of 700 m for 10-15% of test duration. EMROAD splits the input data between moderate and extended conditions and applies the correction described in Regulation EU 2018/1832 by dividing the second-by-second emissions of pollutants (not CO_2) by the value of 1.6. A comparison between the two parameters indicates that the impact of temperature on final results will be much more than that of altitude. As displayed in Figure 14, data in extreme ambient conditions were above 1% in 4 tests which should then be considered invalid while performing type-approval or in-service conformity procedures (data in extreme conditions < 1%).

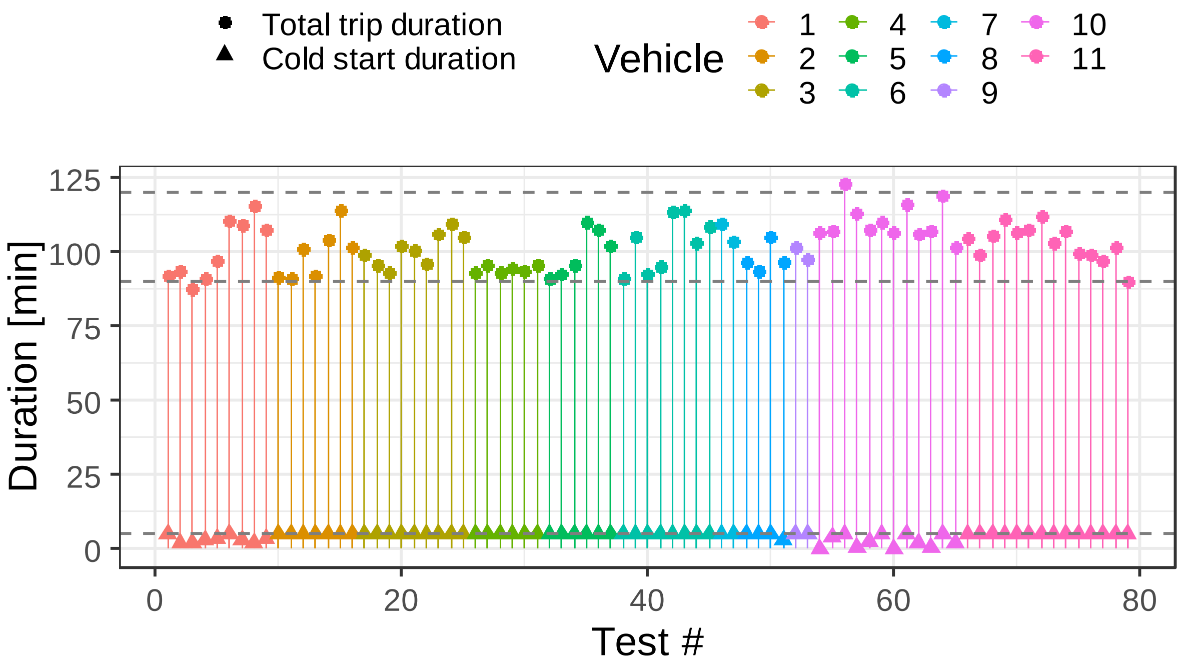
Average speed of the urban, rural and motorway driving modes are plotted in Figure 15 (upper panel) together with the requirement on urban speed. The dataset was characterized by urban speed ≈ 30 km/h, rural speed ≈ 75 km/h and motorway speed ≈ 110 km/h. The motorway mode contains variable percentages of driving above 100 km/h, all with duration above 5 min (requirement on motorway speed), as displayed in the lower panel. Speed less than 1km/h defines the stop mode, which cannot last for more than 15 seconds right after the test starts, and cannot occur for more than 5 consecutive minutes during the trip. None of the tests in our dataset feature idling events longer than 5 minutes, while some tests were characterized by initial idle duration longer than 15 s, but still relatively short (< 40 s) as can be seen in Figure 16.

The second-by-second signal of altitude above sea level was used to calculate the urban and total elevation gain plotted in Figure 17 together with the upper limit of 1200 m/100km, applicable to both. Several trips of vehicles 10 and 11 had larger elevation gain than allowed by the RDE-4 requirements. Those tests were expressly designed to be performed in mountain regions typical for instance of the European Alps.

Two driving parameters describe the dynamics of the RDE trip according to Appendix 7a of Regulation EU 2018/1832, namely the 95th percentile of speed times acceleration (v*a_95) and the relative positive acceleration (RPA). Figure 18 shows the distribution of these parameters against the average vehicle speed separately for urban, rural and motorway speed bins. Several tests overshot the upper threshold for v*a_95 as they were intentionally driven in dynamic mode, while no test was below the lower limit of RPA.

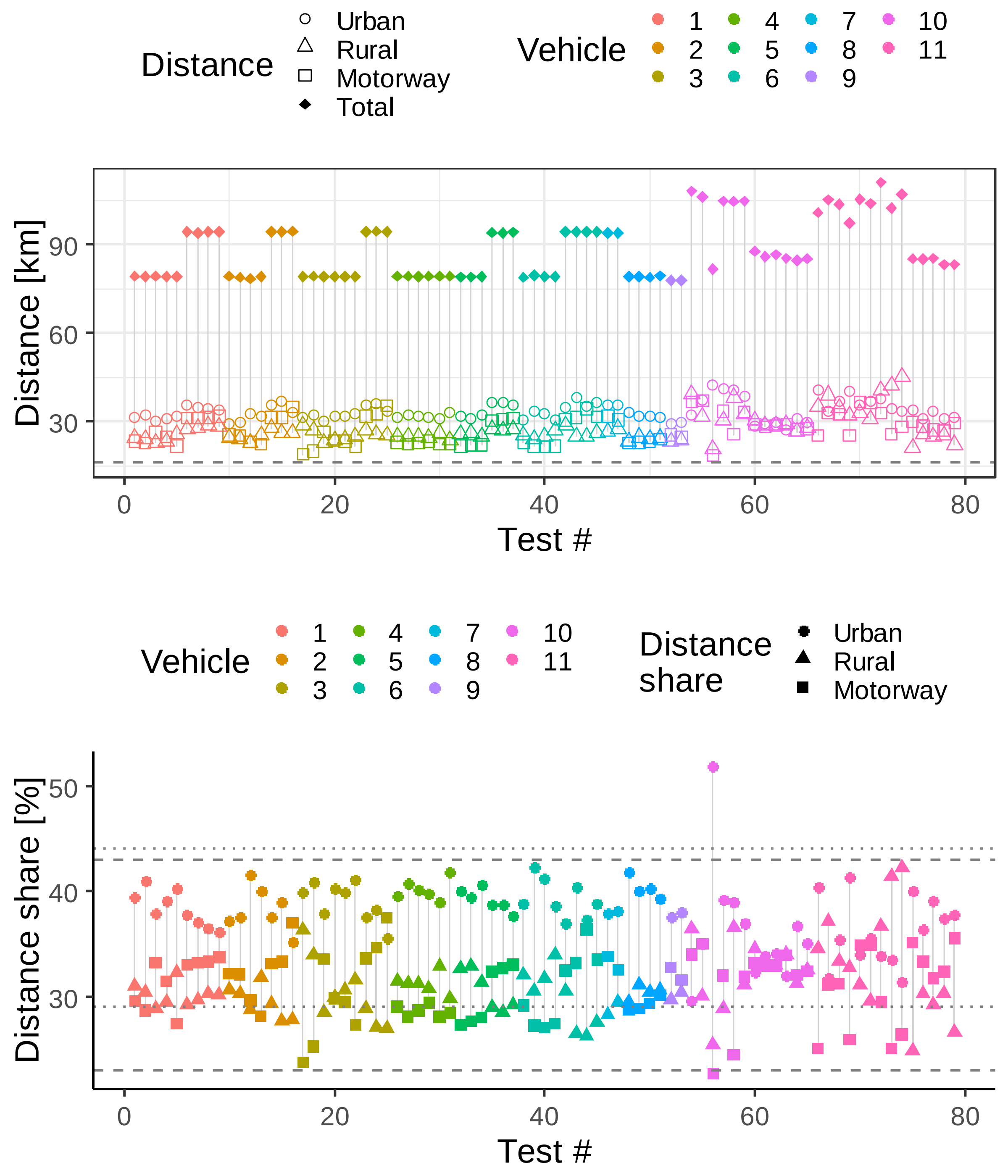
All in all, our dataset generally fulfils the RDE-4 requirements with specific and expected deviations chosen in order to test the EMROAD full capabilities.

Figure 10. Total and cold start trip duration (markers) with delimiting valid ranges (dashed lines): minimum 5 min for the cold start, between 90 and 120 min for the total trip.



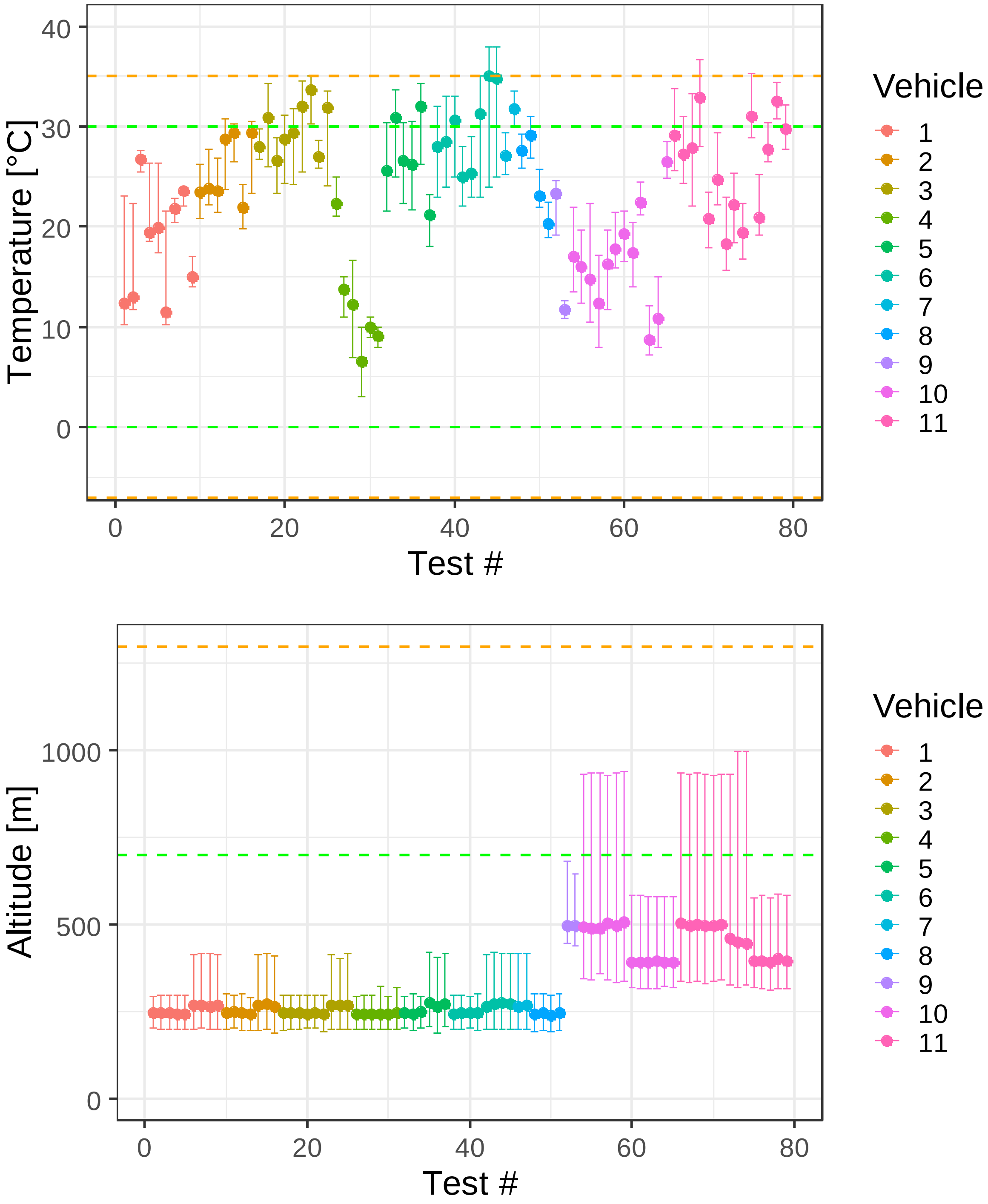
Source: JRC.

Figure 11. Covered distance (upper panel) and distance shares (lower panel) of the urban, rural and motorway parts of the trip. Grey dashed/dotted lines delimit the permissible ranges (minimum 16 km of distance driven, 23-43% of rural and motorway shares, 29-44% of urban share).



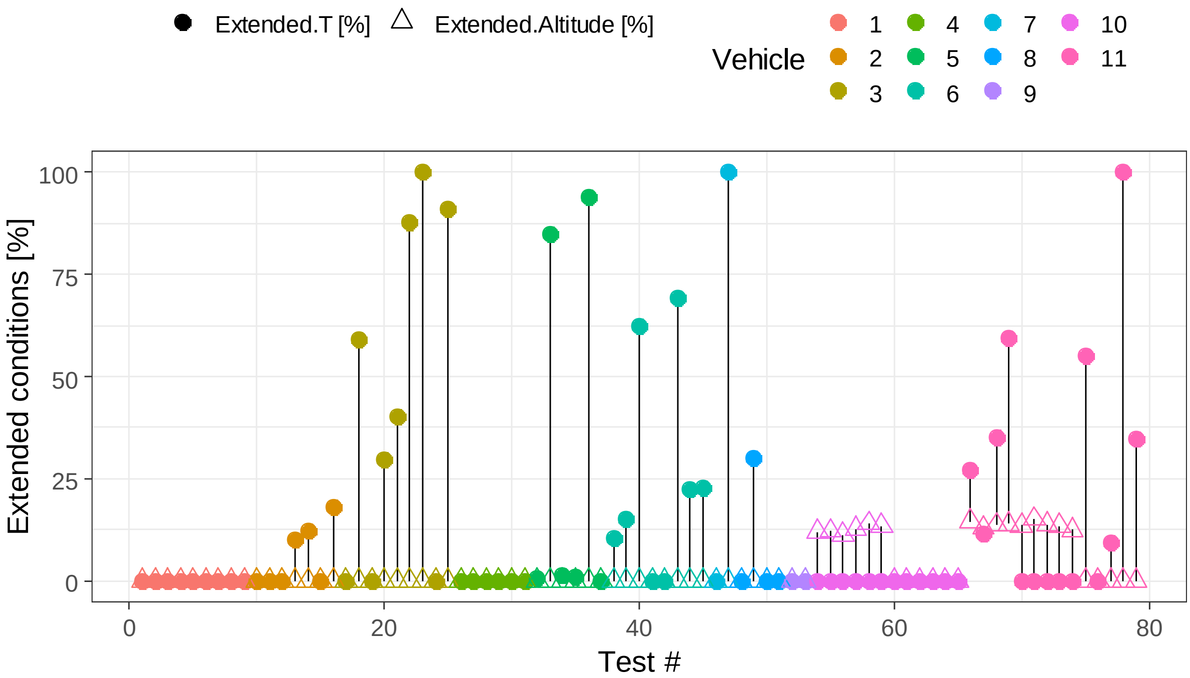
Source: JRC.

Figure 12. Average ambient temperature (upper panel) and altitude (lower panel) of the RDE tests, color-coded by vehicle. Error bars represent minimum and maximum values. Dashed horizontal lines are the boundary values; see text for details.



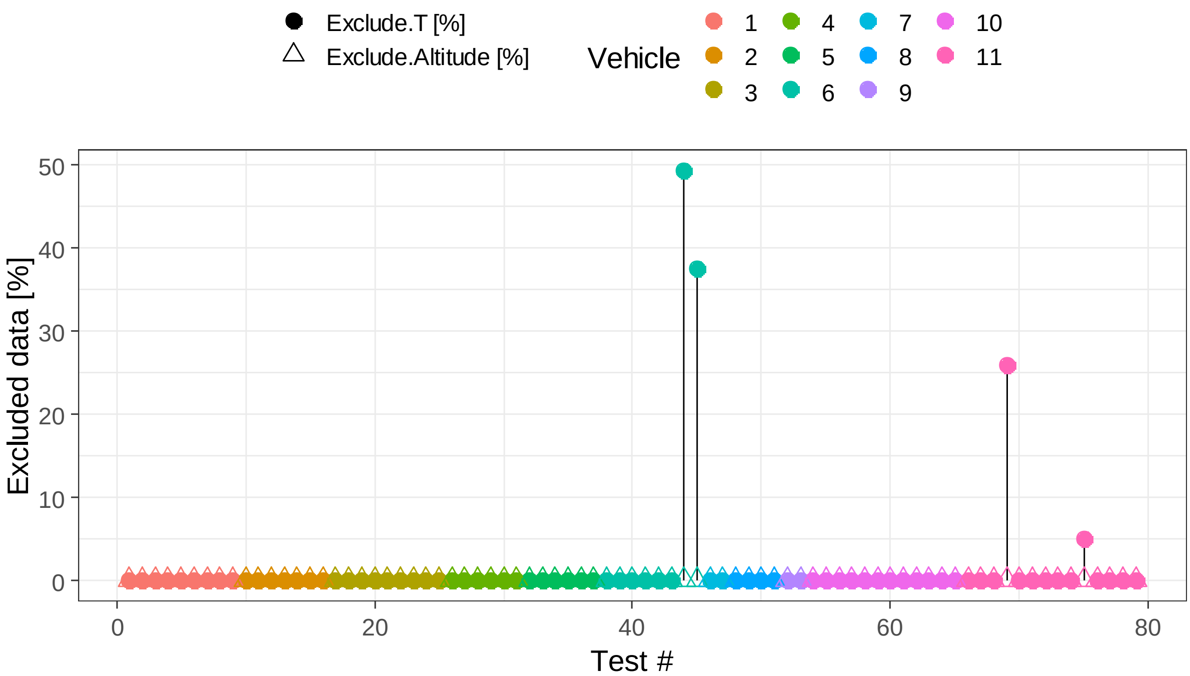
Source: JRC.

Figure 13. Percentage of extended conditions data per test in terms of temperature and altitude, color-coded by vehicle. Extended data belong to the temperature range between 30 ºC and 35ºC (no data was contained in the lower interval, -7 ºC < T < 0 ºC) and to the altitude range 700-1300 m.



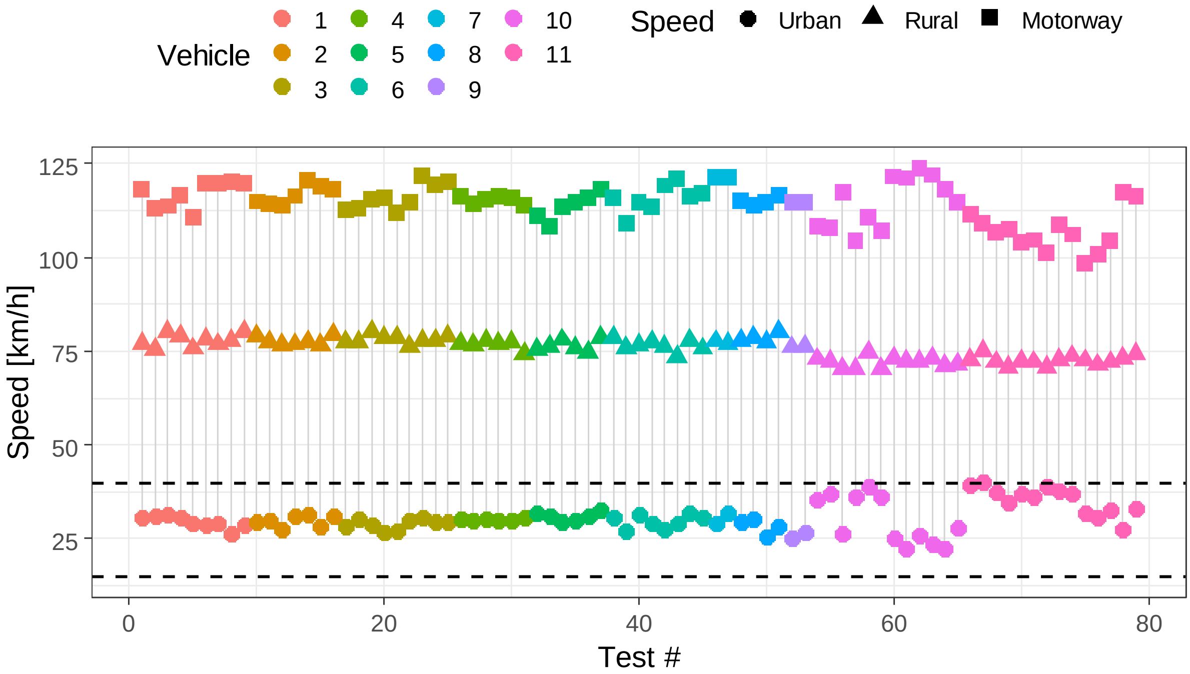
Source: JRC.

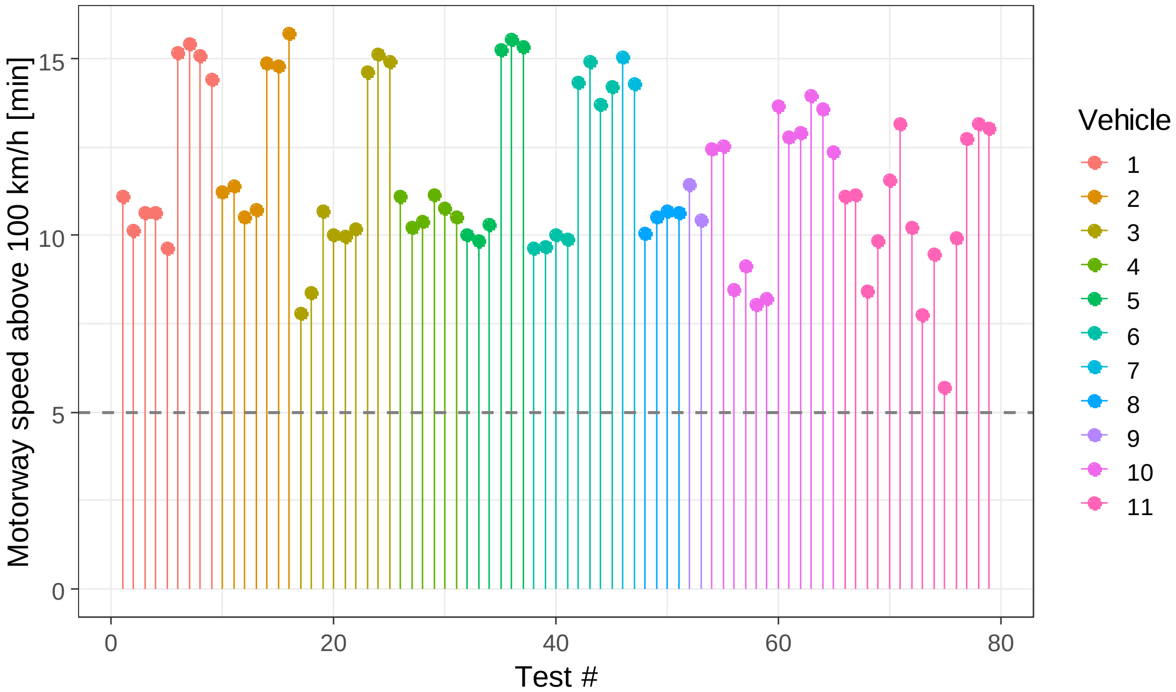
Figure 14. Percentage of data in "extreme" ambient conditions (i.e. outside extended conditions boundaries). Extreme ambient values are above the upper threshold for temperature (35 ºC). No test was conducted above the upper threshold for altitude (1300 m).



Source: JRC.

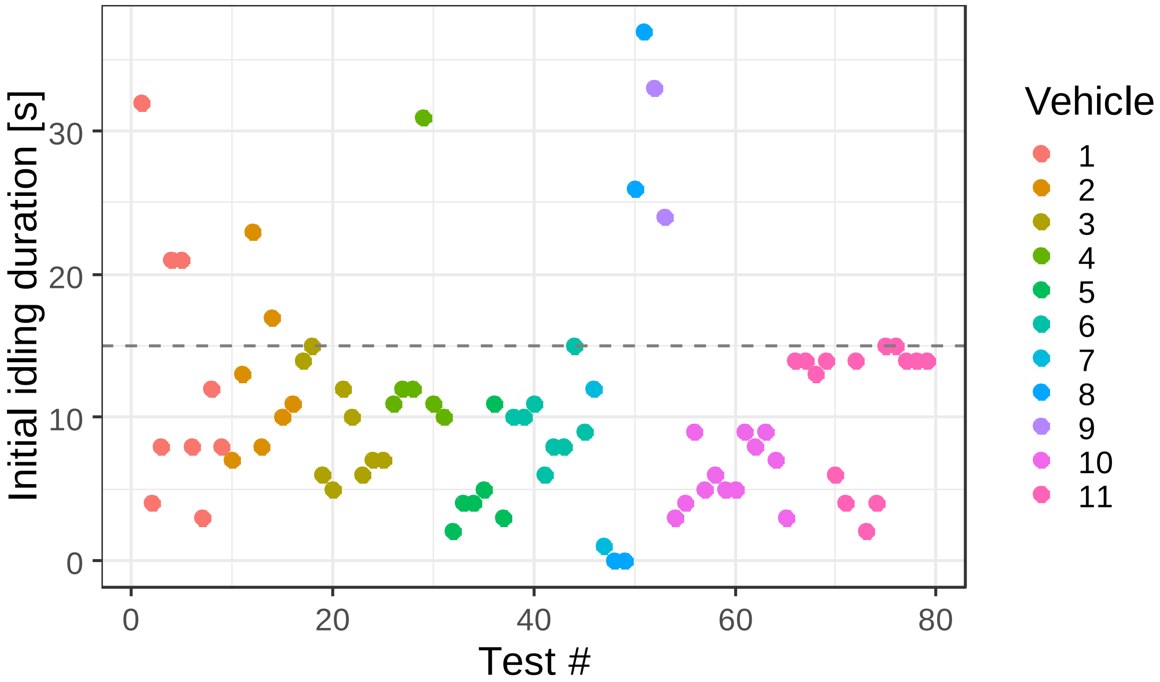
Figure 15. Upper panel: Average speed per test by driving mode. Dashed lines define the permissible range of urban average speed (15-40 km). Lower panel: time spent at speed above 100 km/h during motorway driving (minimum = 5 minutes).





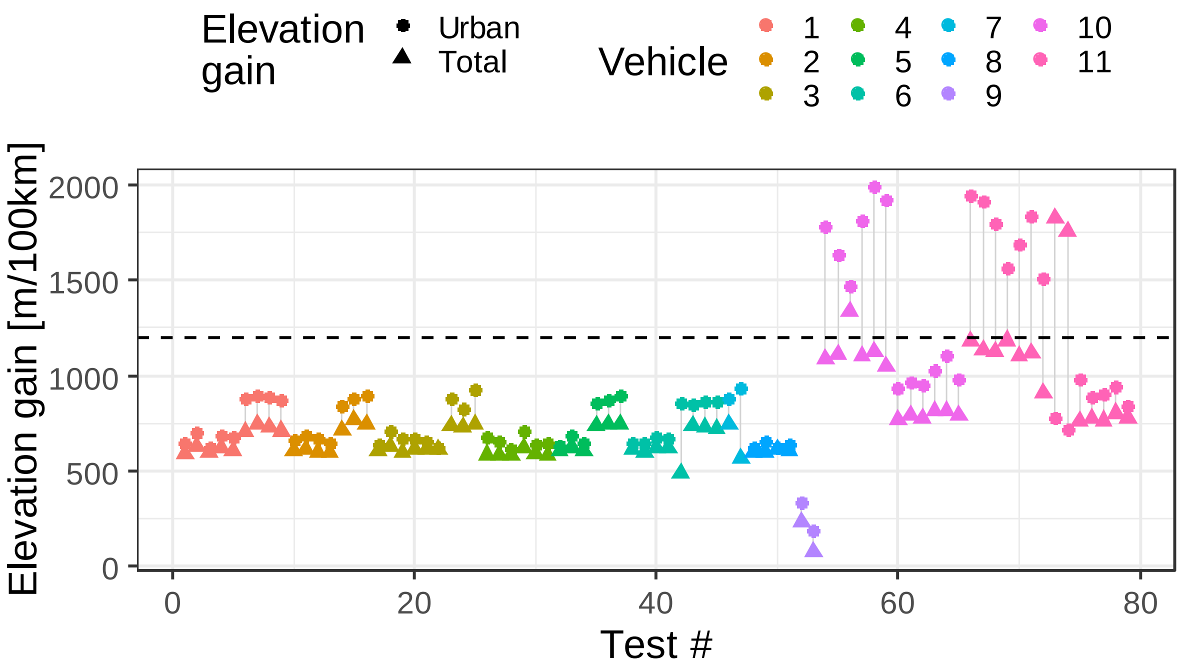
Source: JRC.

Figure 16. Duration of the initial idling after the test start.



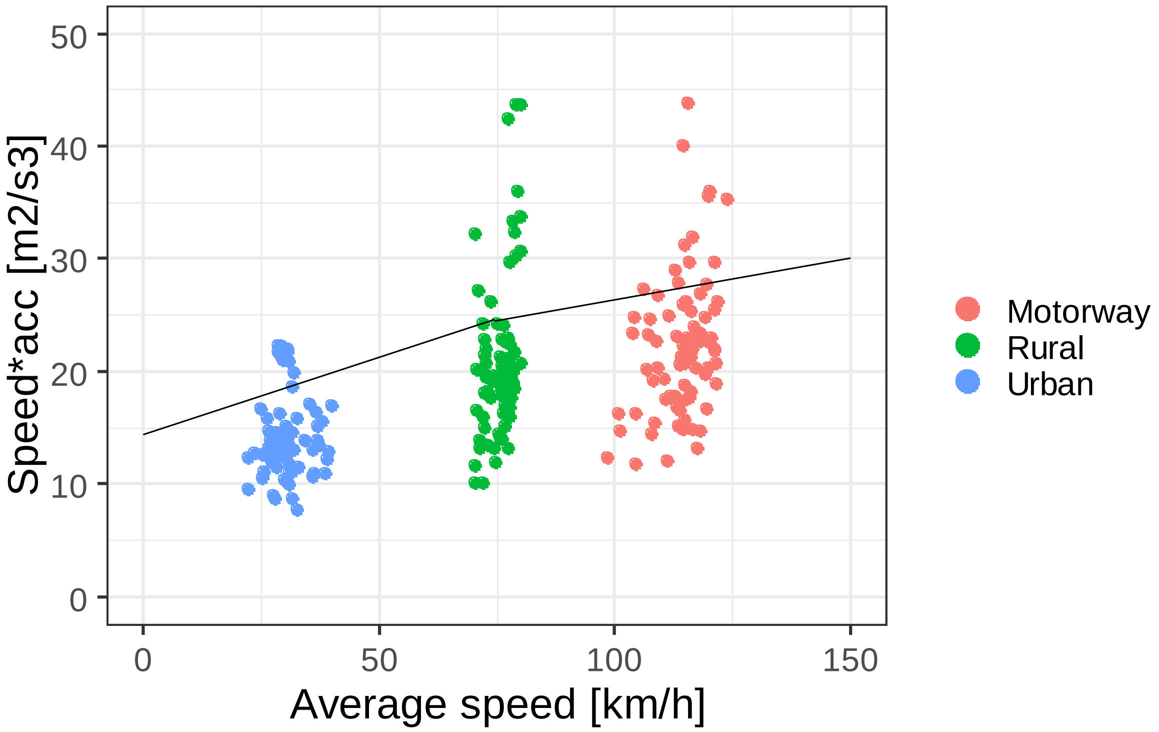
Source: JRC.

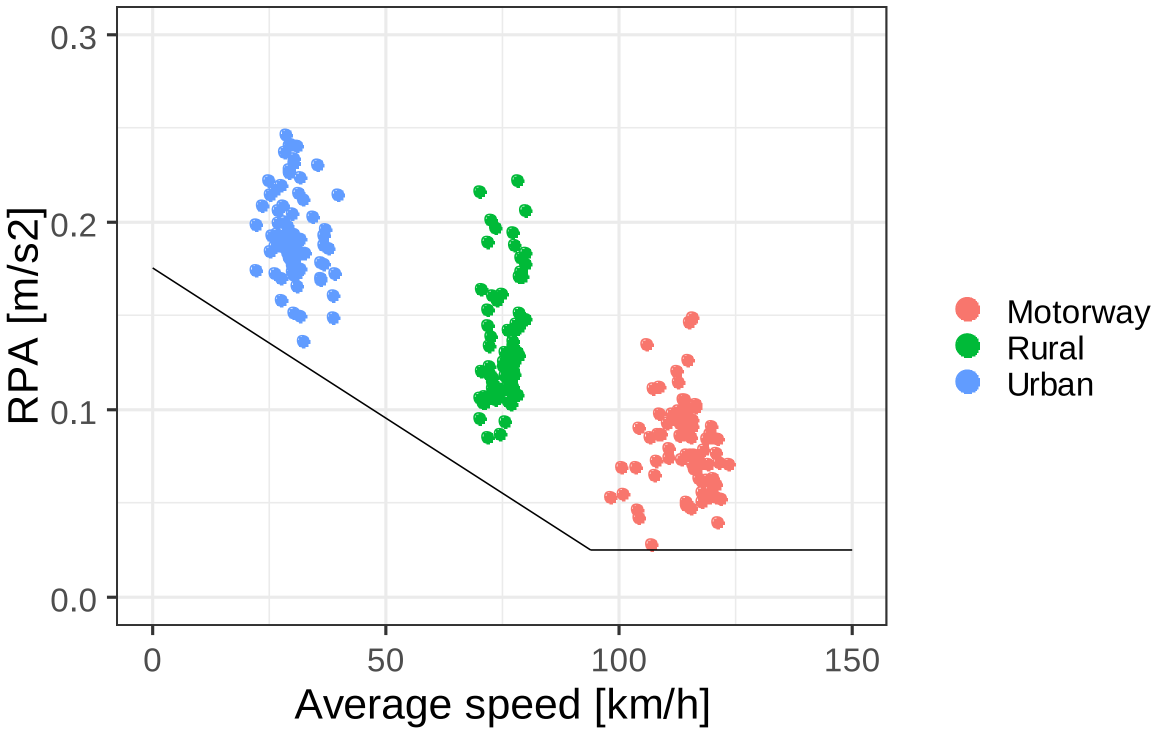
Figure 17. Total and urban cumulative positive elevation gain. Maximum allowed gain = 1200 m/100km (dashed line).



Source: JRC.

Figure 18. Distribution of the dynamic parameters v*a_95 (upper panel) and RPA (lower panel) against average speed of the urban, rural and motorway part of the trip.





Source: JRC.

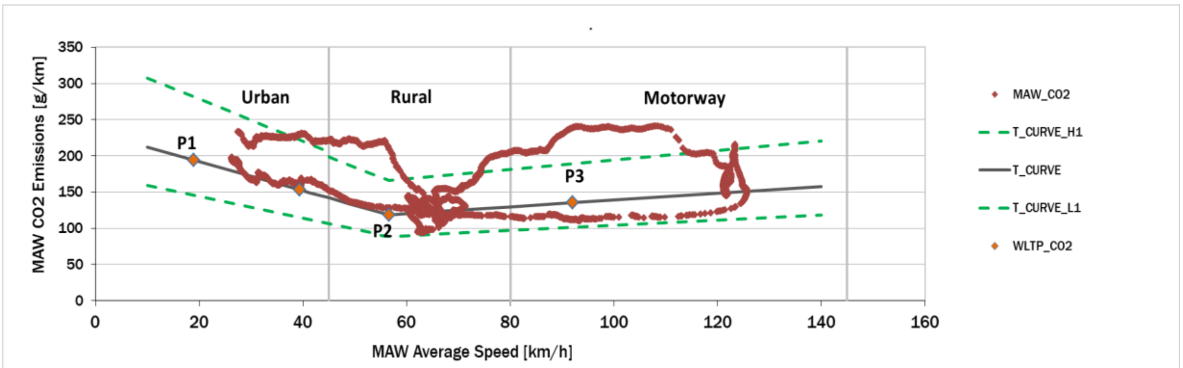
4 Optimization of the CO_2 characteristic curve and tolerances

4.1 Definition of the characteristic curve

During the first RDE stages (i.e. up to RDE-3), the vehicle reference CO_2 emissions measured on the WLTP were in many cases obtained with unrealistic road load settings. As a consequence, the EU RDE legislation imposed corrective coefficients for the points P1, P2, P3 used to build the CO_2 characteristic curve described below. These coefficients were set to 1.25, 1.10 and 1.05 respectively for P1, P2 and P3. Following the enforcement of Regulation EU 2017/1151, the data collected during the RDE "monitoring phase" demonstrated clearly that the initial data used to propose the initial RDE settings and the corrective coefficients were biased. After analysis of the RDE monitoring data and the data of the present study, it was proposed to use the real WLTP CO_2 values without any correction.

As shown in Figure 19, the CO_2 distance specific emissions versus average speed of the moving average windows are scattered around the CO_2 characteristic curve built on reference points P1, P2 and P3 at average speeds of 18.882, 56.664 and 91.997 km/h, respectively. The points correspond to the Low, High and Extra High parts of the WLTP driving cycle as specified in Regulation EU 2018/1832 and each MAW CO_2 data point is the result of integrated emission values over the specific window time. The speed domain of the MAW is further subset to define the urban, rural and motorway windows: 0-45 km/h (urban), 45-80 km/h (rural), and 80-145 km/h (motorway). The scatter of CO_2 emission values must fulfil the requirements described in 5.1 ([8]).

Figure 19. Moving averaging windows (red dots) plotted on top of the CO_2 characteristic curve (black line) and tolerances (green dashed lines) for vehicle 10, Test 60.



Source: JRC.

(8) Note that the definition of urban, rural and motorway window is different from the definition of rural, urban and motorway operations of an RDE trip used for results binning and verification of trip dynamics as explained in paragraph 5.1.

4.2 Tolerances (RDE-4)

The overall trip dynamics were verified with EMROAD, according to Appendix 5 of Regulation EU 2018/1832 (detailed criteria presented in chapter 5). The CO_2 characteristic curve is enveloped in prescribed tolerances and the share of normal windows (i.e., those within the tolerances) be above 50% for each of the urban, rural, and motorway part of the trip; see Table 7 for detailed tolerances.

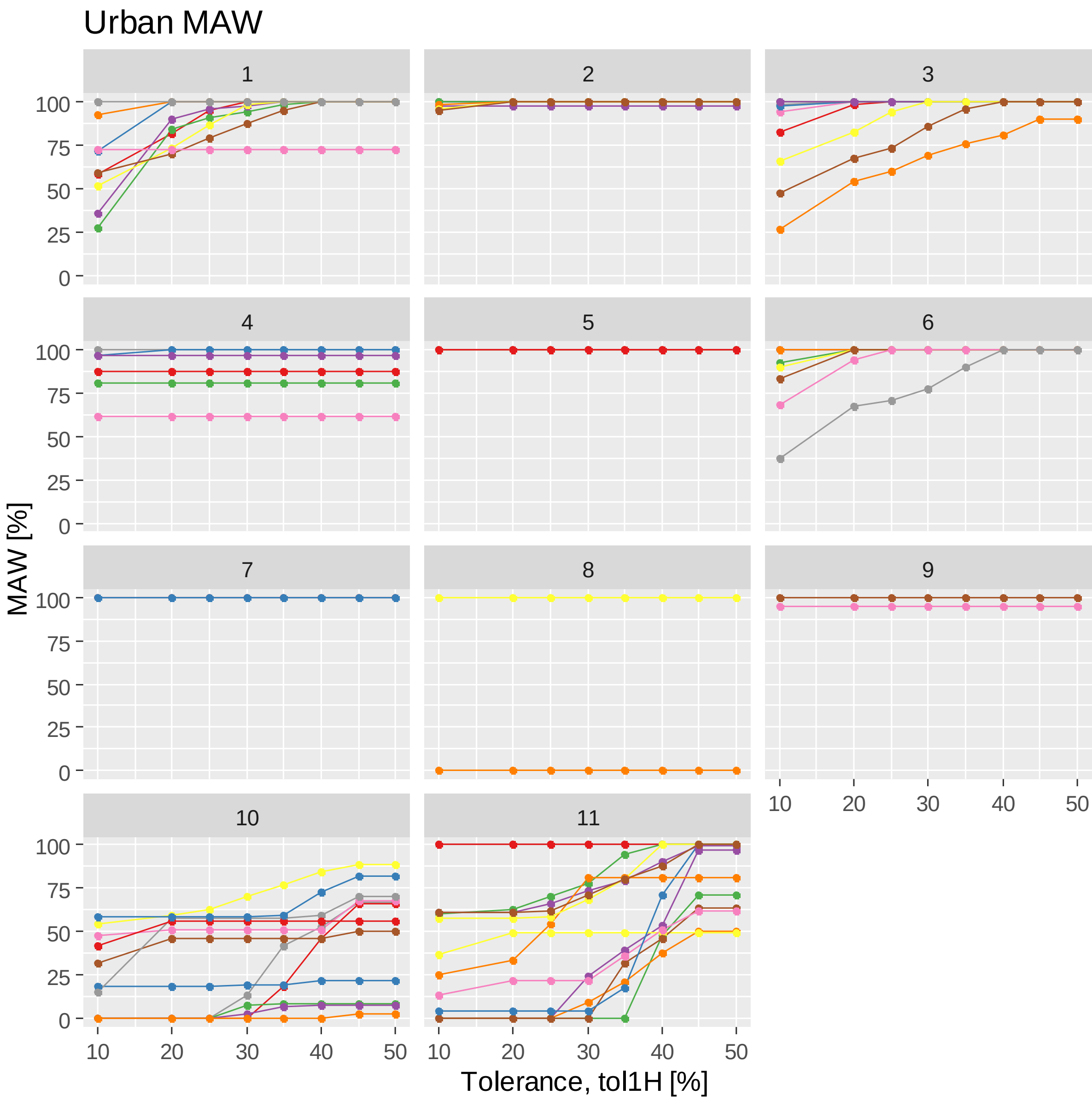
The JRC dataset was used to test the sensitivity of the Moving Average Windows (MAW) method to increasing upper tolerance values (referred to as tol_{1H}) from 10% up to 50%. Results are presented for urban, rural and motorway driving in Figure 20, Figure 21 and Figure 22, respectively. The share of normal windows generally increases for increasing upper tolerance tol_{1H}. For some tests and vehicles it remains constant indicating that the windows were already contained in the tolerance band with tol_{1H} equal to default values as in Table 7, or windows were outside the lower tolerance. These type of graphs are useful when the fine tuning of tolerances is required for legislation revision and assessment, and for the extension of the EU-RDE method to extra-EU countries with different or under development settings. The amount of information contained is condensed in Figure 23 where the share of valid tests with respect to moving averaging windows requirements (see Table 8) is plotted against the variable upper tolerance tol_{1H} broken down into urban, rural and motorway modes. In our case, the validity is particularly sensitive to little changes of the upper tolerance applicable to the motorway mode, indicating that much of the motorway driving is characterized by overall dynamics (in terms of CO_2) close to that of the Extra High phase of a WLTC test. With an upper tolerance of just 20% (legislative = 40%) more than 80% of tests would be valid in terms of share of motorway windows. More critical is the behaviour of urban and rural windows: they invalidate many more tests than the motorway windows and the rate of validation is lower indicating that an upper tolerance of at least 40-45% is needed in order to maximize the number of valid tests. Based on similar considerations, the policy maker can assess the relation between chosen tolerances and share of valid tests from a dataset in terms of overall trip dynamics and can identify which driving mode deserves more in-depth analysis.

Table 7. Average speed conditions defining urban, rural and motorway driving and associated tolerances above and below the CO_2 characteristic curve (upper and lower tolerances referred to as tol_{1H} and tol_{1L} in Regulation EU 2018/1832).

Parameter	Unit	Urban	Rural	Motorway
Average Speed	km/h	< 45	$45 < \bar{v} < 80$	$80 < \bar{v} < 145$
Upper tolerance	%	45	40	40
Lower tolerance	%	25	25	25

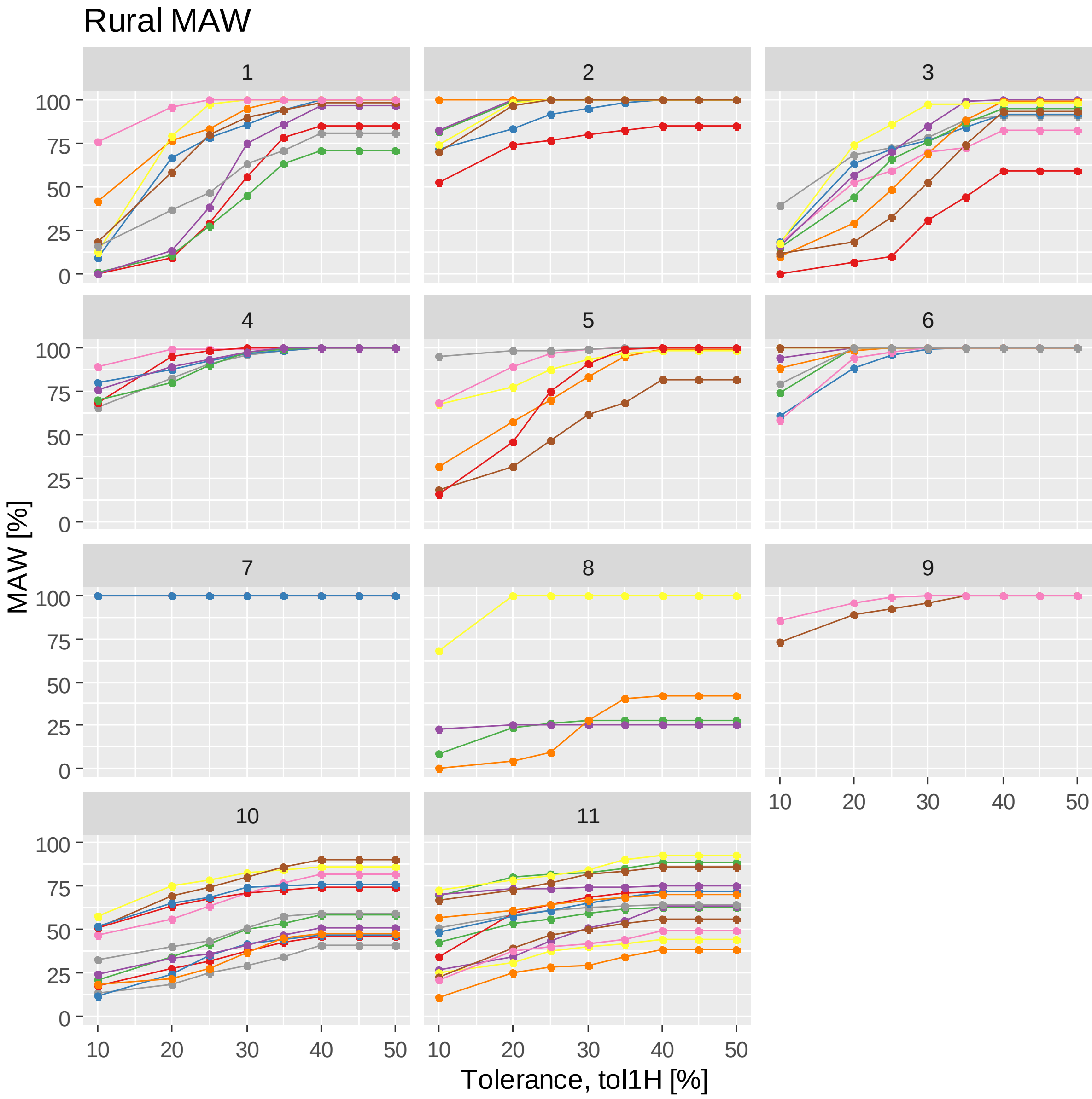
Source: JRC.

Figure 20. Share of normal urban MAW (speed of the window < 45 km/h) against variable tolerance values. Panels refer to vehicles 1 to 11. Each line represents 1 test.



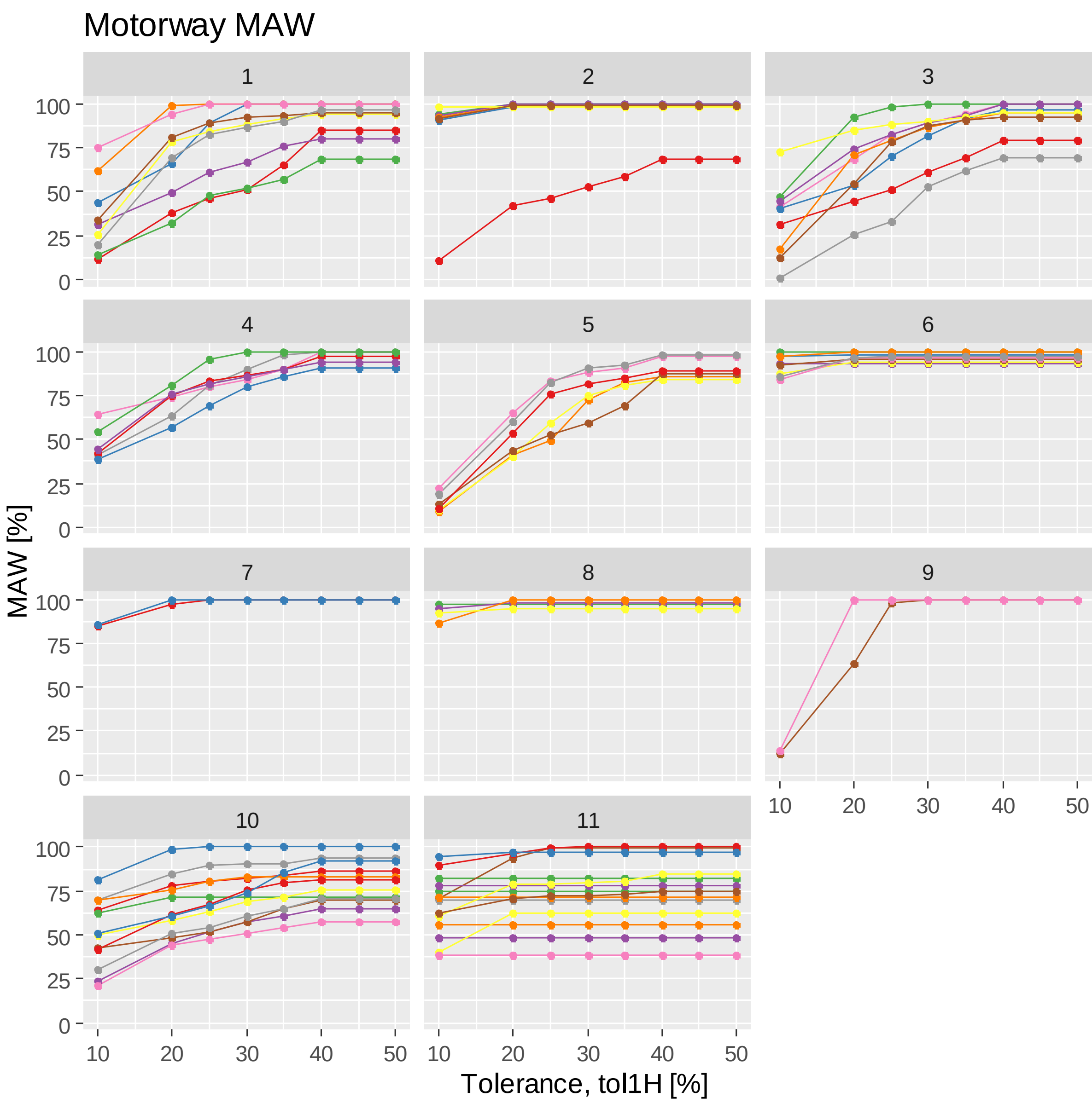
Source: JRC.

Figure 21. Share of normal rural MAW (speed of the window between 45 km/h and 80 km/h) against variable tolerance values. Panels refer to vehicles 1 to 11. Each line represents 1 test.



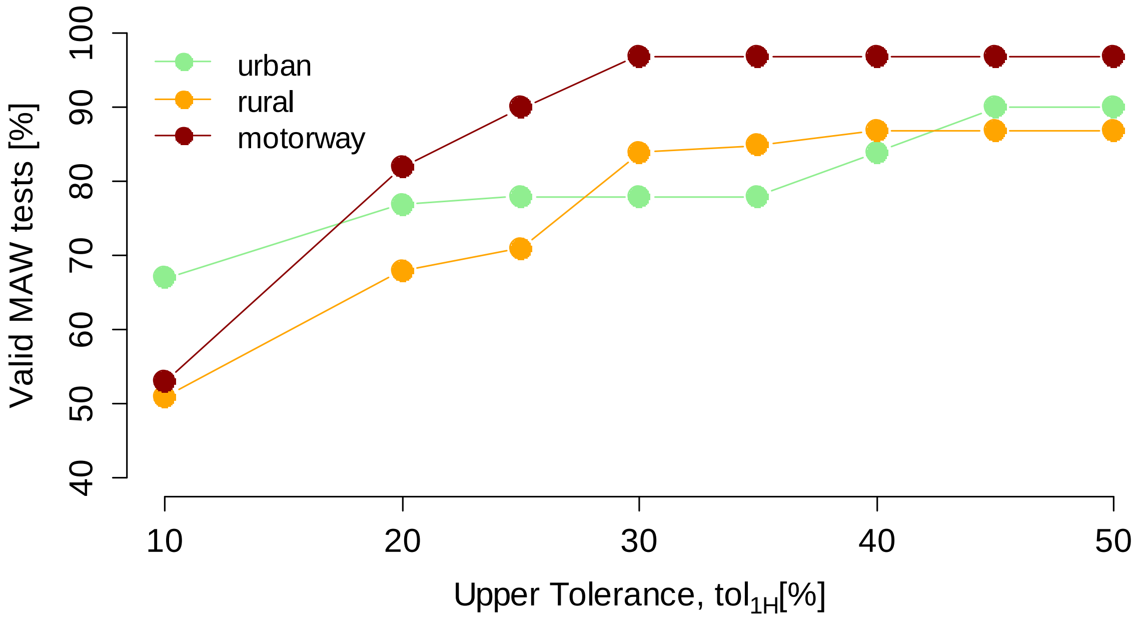
Source: JRC.

Figure 22. Share of normal motorway MAW (speed of the window between 80 km/h and 145 km/h) against variable tolerance values. Panels refer to vehicles 1 to 11. Each line represents 1 test.



Source: JRC.

Figure 23. Share of valid tests in terms of MAW against variable upper tolerance from 10% up to 50%.



Source: JRC.

4.3 Effect of RDE-3/RDE-4 settings on the CO_2 characteristic curve

CO_2 emission from an RDE test are scattered around the CO_2 characteristic curve built with the WLTP test results as shown in Figure 19. The ratio, r_i (where i is the specific window) between the CO_2 obtained with the MAW method after an RDE trip and the CO_2 of the characteristic curve is used as a measure of the overall trip dynamics. It is informative to investigate the statistical distribution of this ratio over the entire speed range and then to apply the requirements of either the RDE-3 or the RDE-4 legislative package (Regulation EU 2017/1151 and Regulation EU 2018/1832, respectively).

The shape of the r_i distribution depends by many factors such as vehicle, driving style, trip composition, etc.. Figure 24 shows the distribution of the r_i ratio for vehicle 1, test 2. Most of the urban and total MAW points are contained in the region delimited by the tolerances; hence the test is valid in terms of MAW requirements (50% of MAW within tolerances for the urban, rural and motorway parts separately). However, RDE trips can be design such that the r_i ratio deviates considerably from the tolerances without affecting the trip validity in terms of MAW, as can be seen in Figure 25. In some parts of the trip, the vehicle produced about 7 times the CO_2 of the WLTC at similar speed because of a combination of quick elevation changes and aggressive driving. In fact, other requirements for the excess or absence of dynamics or for the cumulative elevation gain invalidate the test, but not the MAW requirements. A second example in Figure 26 shows the same behaviour with large deviations from the characteristic curve. However, only the cumulative altitude gain requirement was violated. The examples demonstrate that the combination of several checks, and possibly some degree of redundancy, during the post-processing of RDE data is needed in order to assure that the vehicle is driven in normal condition of use. In other words, no requirement should be dropped in future legislation developments without careful cross-check of test validity.

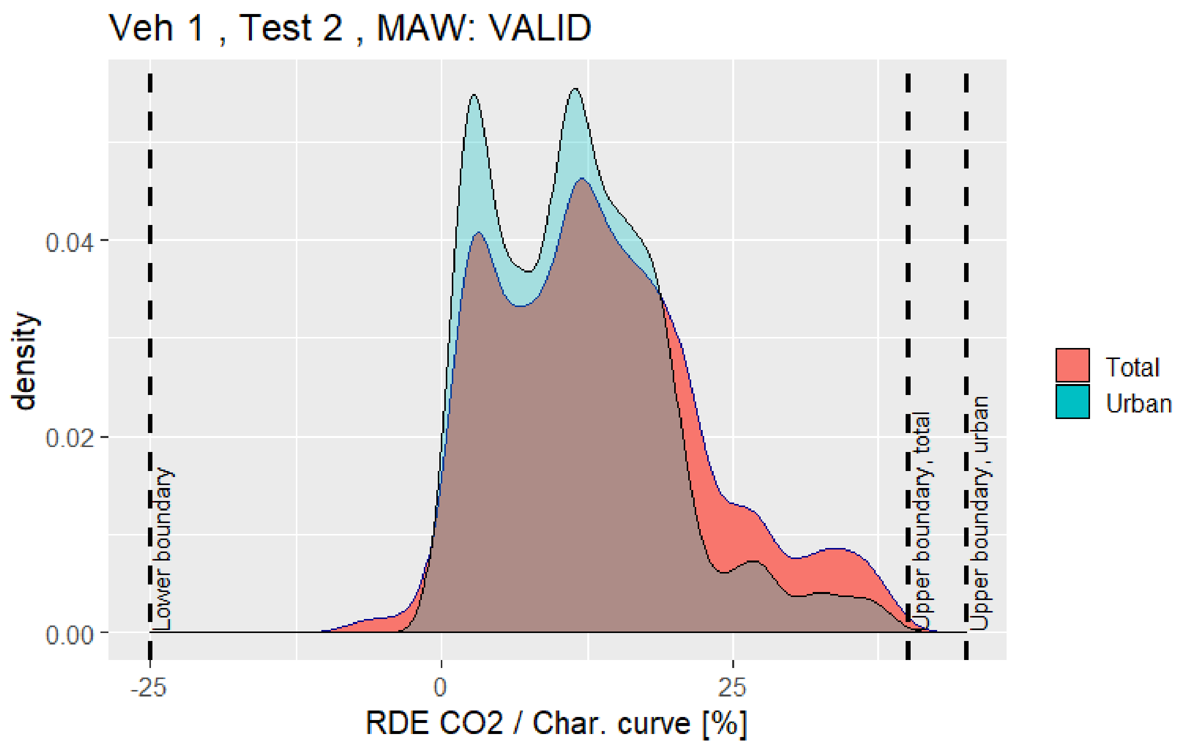
Figure 27 shows the distribution of the r_i ratio for Test 8 of vehicle 1. The characteristic curve built with CO_2 WLTC values is compared with the RDE-3 CO_2 (red curve) and RDE-4 CO_2 (black curve) values and tolerances (vertical dotted lines) delimiting the normality of the windows. The two distribution patterns are very similar, but horizontally displaced of about 10 percent points, with the RDE-4 curve associated with larger ratio and hence larger RDE CO_2. As a result, the RDE test analyzed with the RDE-3 method would be invalid in terms of the MAW requirements of RDE-4. The same test is instead valid when analyzed with the RDE-4 method. Summarizing the same comparison for all trips in the dataset as in Figure 28 it can be inferred that:

— RDE-4 CO_2 is always larger than the CO_2 calculated with the RDE-3 method;

— 25% of tests became valid in terms of overall trip dynamics (based on the MAW method) when passing from the RDE-3 to the RDE-4 analysis. The opposite never occurred, i.e. no RDE-3 valid test became invalid after the RDE-4 analysis.

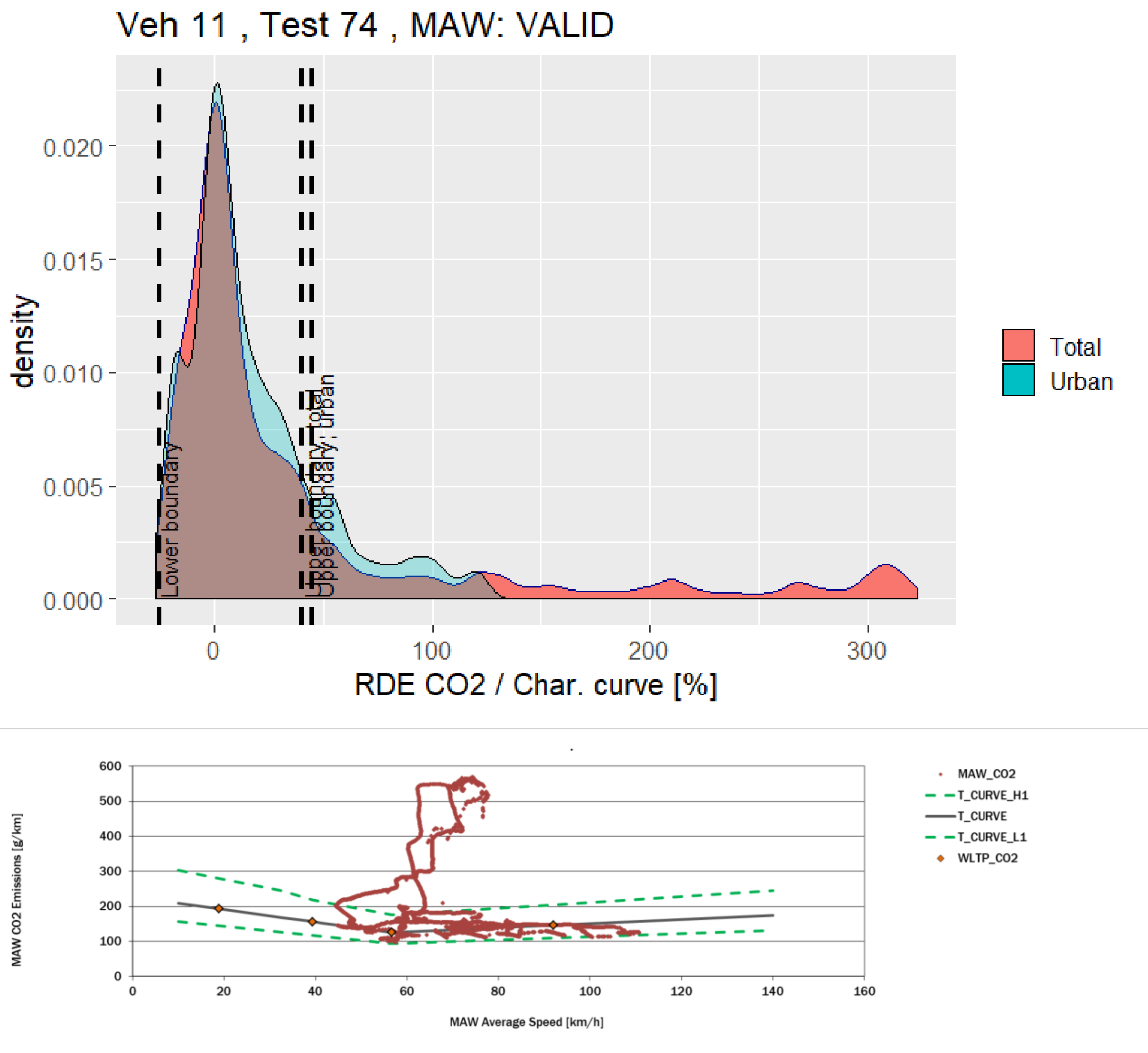
By averaging on the entire dataset, the mean distance between RDE-4 CO_2 and the CO_2 of the characteristic curve (Figure 28) was about +10%. This does not necessarily mean that the WLTC is too mild to represent the normal conditions of vehicle use. In fact, several tests were invalid either due to the MAW normality, or to the excess of trip dynamics, or to trip characteristics such as the cumulative altitude gain. However, it is evident that vehicles can be driven in conditions more severe than the WLTC, especially in regions with frequent uphill and downhill driving. These driving conditions are not covered by the present legislation. Preliminary discussions on the shape of the post Euro 6 legislation are highlighting the need of clean and efficient vehicles in all possible conditions of use. A metrics would be desirable in order to measure the weight of MAW points outside (mainly above) tolerances.

Figure 24. Distribution of the ratio between RDE-CO_2 and the CO_2 of the characteristic curve.



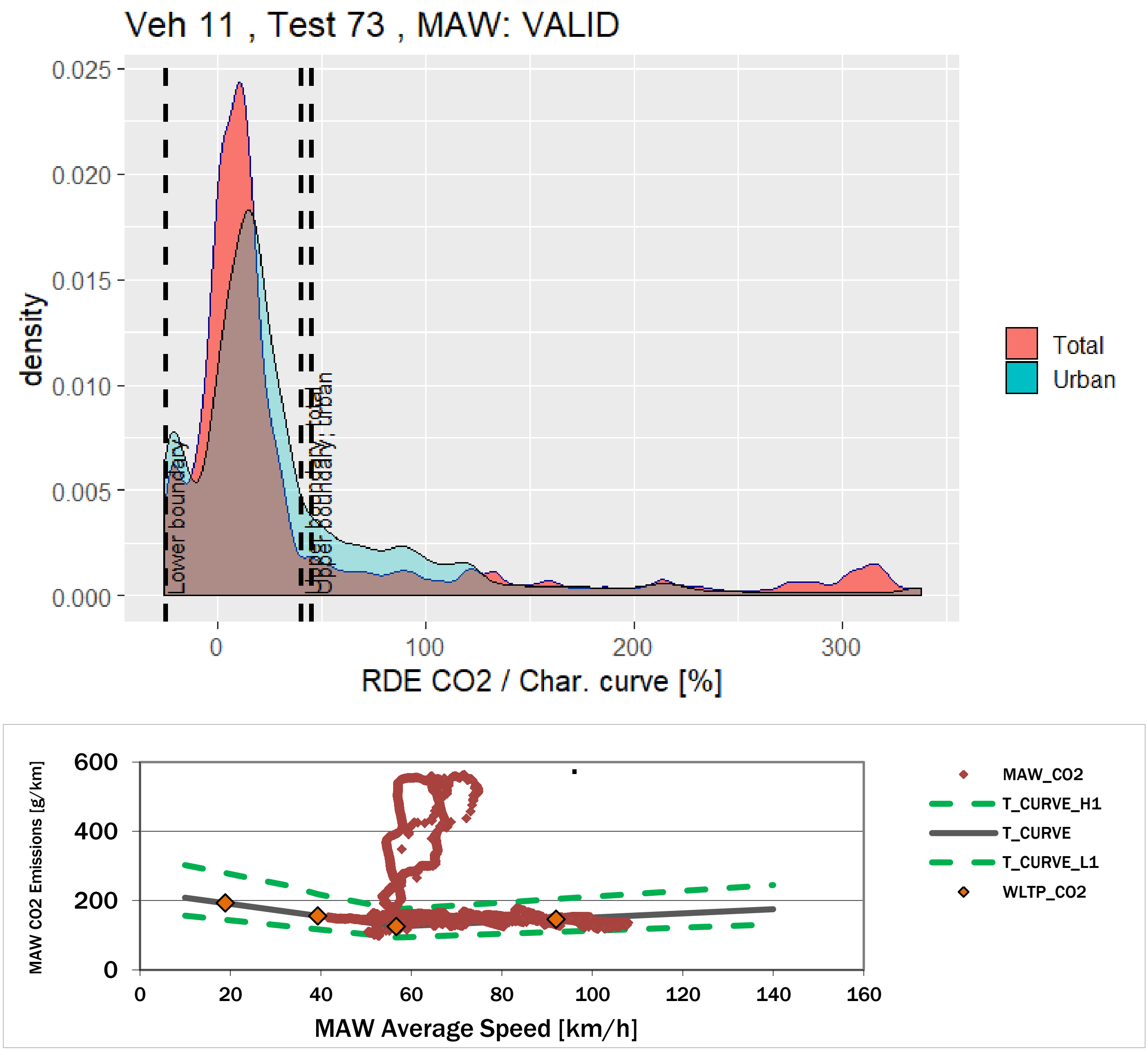
Source: JRC.

Figure 25. Distribution of the ratio between RDE CO_2 and characteristic curve CO_2 (upper panel) for a valid test in terms of MAW, but with extreme overshooting of the upper tolerance. See also the lower panel with explicit RDE CO_2 points and characteristic curve. The test non-validity was preserved by dynamics = invalid and elevation gain = invalid.



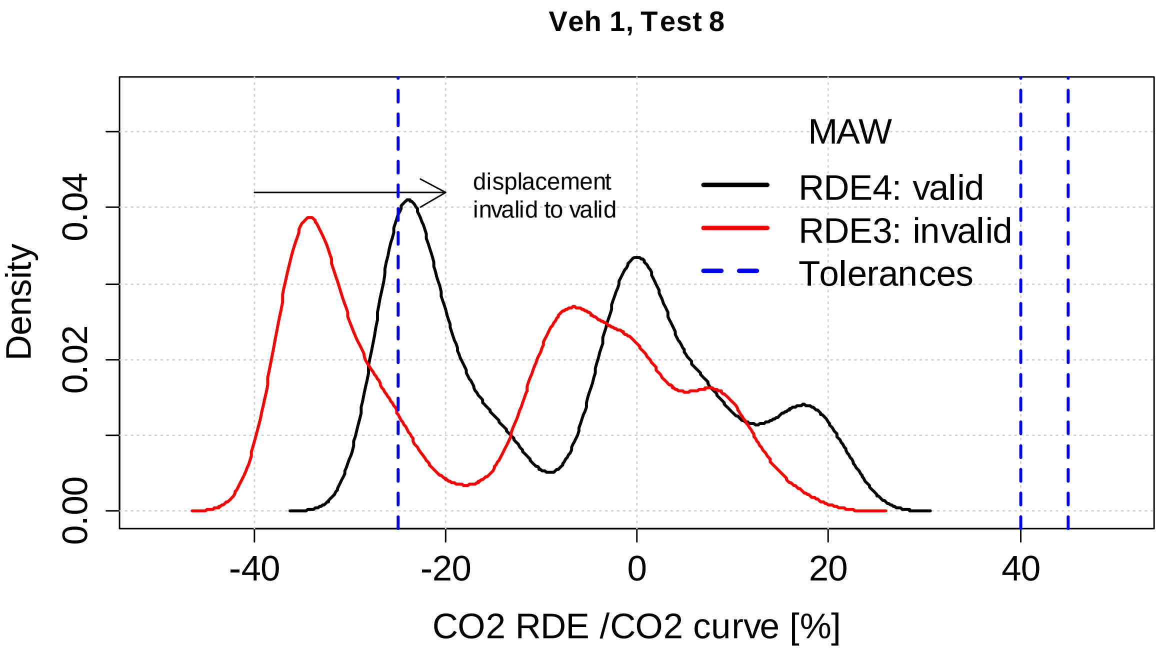
Source: JRC.

Figure 26. Example of valid test in terms of MAW but with extreme overshooting of upper tolerance (preserved by elevation gain = invalid).



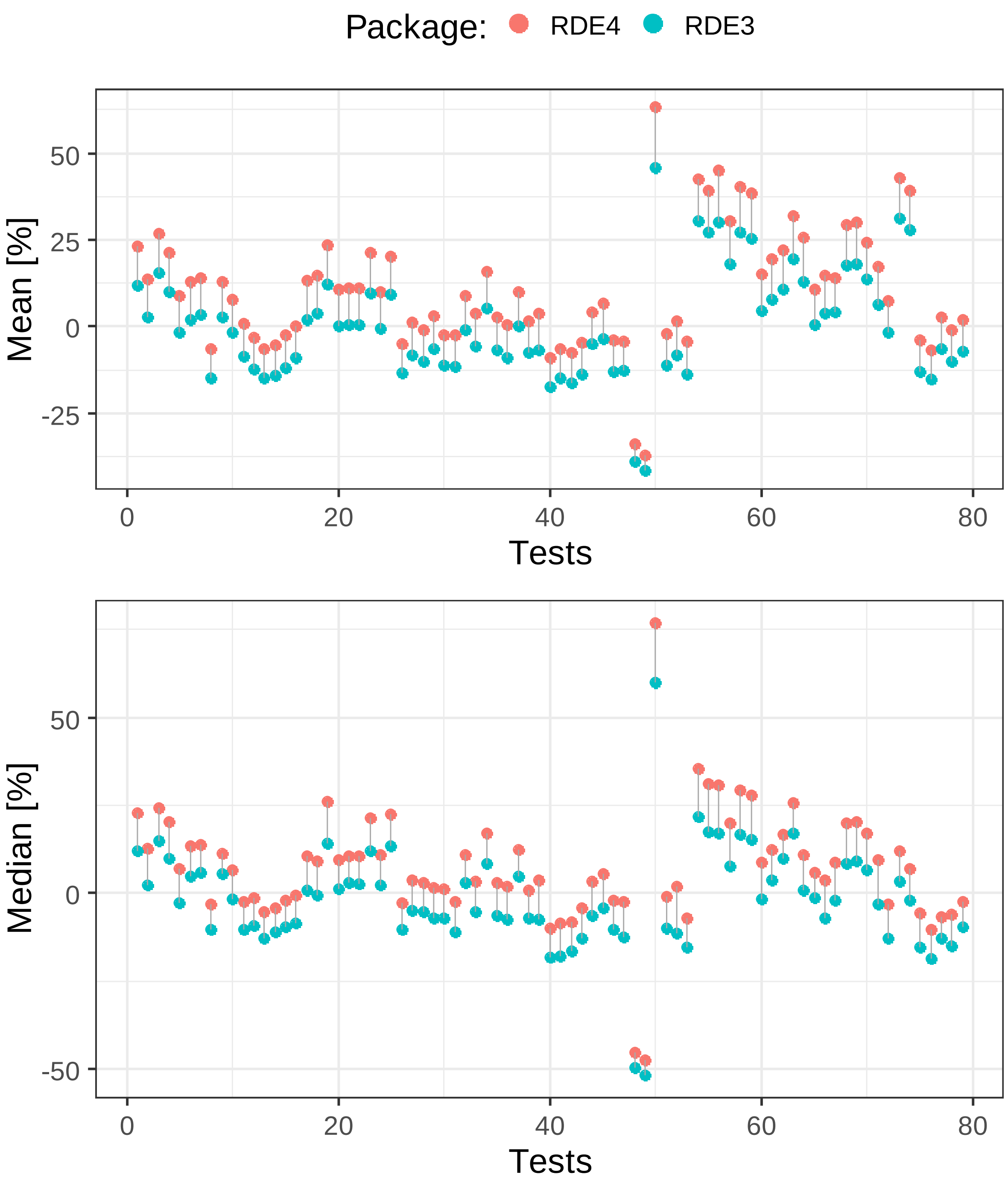
Source: JRC.

Figure 27. Distribution of the ratio between the RDE CO_2 and the CO_2 characteristic curve with legislation provisions of the RDE-4 or the RDE-3 package.



Source: JRC.

Figure 28. Mean (upper panel) and median (lower panel) of the distribution of the distance from the CO_2 reference curve.



Source: JRC.

5 Final assessment of trip validity

5.1 Methodology

The validity of an RDE tests (trip validity) was evaluated with the three-step procedure described in Regulation EU 2018/1832 and summarized in Figure 9. The trip validity requirements checked by EMROAD are detailed in Table 8 and grouped by type: general, trip characteristics, cold start, MAW, and dynamics. EMROAD checks the test validity also in terms of emission compliance for NOx and PN (separately for urban and total parts of the trip). However, as explained in paragraph 2.4, the actual amount of emissions is not in the scope of the present Report: vehicles were not subject to RDE type-approval when registered, nor necessarily to the WLTP. For the purpose of this Report (exploring the RDE boundaries without type-approval or market surveillance implications), we consider the groups summarized in Table 9: trip characteristics (group 1 and 2), excess/absence of trip dynamics, and overall dynamics via the MAW method.

Trip characteristics group 1 consists of (Annex IIIa, Regulation EU 2018/1832):

— Urban distance

— Rural distance

— Motorway distance

— Urban distance share

— Rural distance share

— Motorway distance share

Trip characteristics group 2 consists of (Appendix 7b of Regulation EU 2018/1832):

— Start and end points elevation absolute difference

— Total cumulative positive elevation gain

— Urban cumulative positive elevation gain

Excess/absence of trip dynamics consists of (Appendix 7a of Regulation EU 2018/1832):

— Urban RPA (relative positive acceleration)

— Rural RPA

— Motorway RPA

— Urban 95th percentile Speed*Acceleration

— Rural 95th percentile Speed* Acceleration

— Motorway 95th percentile Speed* Acceleration

— Counts > 100 separately for urban, rural, motorway

Providing that urban, rural, motorway counts are each above 100, the excess/absence of dynamics is determined by the position of 6 data points (3 for RPA, 3 for speed*acceleration) obtained relative to limit curves built as explained in Appendix 7a of Regulation EU 2018/1832.

Overall trip dynamics through the MAW method consists of (Appendix 5, Regulation EU 2018/1832):

— Share of normal urban windows

— Share of normal rural windows

— Share of normal motorway windows

Table 8. Detailed requirements for trip validity adapted from the EU RDE-4 package. Requirement types: G= general, TC, TC1 and TC2 = trip characteristics (subgroup TC1 and TC2 used in the analysis), CS = cold start, MAW = moving average window, D = dynamics.

Requirement	Type	Unit	Requirement
Total trip duration	G	min	[90-120]
Cold start duration	G	min	= 5
Data in extreme conditions	G	%	<1
Urban distance	TC1	km	> 16
Rural distance	TC1	km	> 16
Motorway distance	TC1	km	> 16
Urban distance share	TC1	%	[29-44]
Rural distance share	TC1	%	[23-43]
Motorway distance share	TC1	%	[23-43]
Urban average speed	TC	km/h	[15-40]
Motorway speed above 145 km/h	TC	%	< 3% motorway time
Motorway speed above 100 km/h	TC	min	≥5
Idling event(s) longer than 300 s	TC	-	No
Initial idling duration	TC	s	≤ 15
Urban stop time	TC	%	[6-30]
Start-end elevation absolute difference	TC2	m	≤ 100
Total cumulative positive elevation gain	TC2	m/100km	< 1200
Urban cumulative positive elevation gain	TC2	m/100km	< 1200
Cold start average speed	CS	km/h	[15-40]
Cold start maximum speed	CS	km/h	< 60
Cold start stop time	CS	s	≤ 90
Share of normal urban windows	MAW	%	> 50
Share of normal rural windows	MAW	%	> 50
Share of normal motorway windows	MAW	%	> 50
Urban RPA	D	m2/s2	Pass/Fail(1)
Rural RPA	D	m2/s2	Pass/Fail
Motorway RPA	D	m2/s2	Pass/Fail
Urban 95th percentile Speed*Acc	D	m2/s3	Pass/Fail(2)
Rural 95th percentile Speed*Acc	D	m2/s3	Pass/Fail
Motorway 95th percentile Speed*Acc	D	m2/s3	Pass/Fail
Number of counts - Urban	D	-	≥100
Number of counts - Rural	D	-	≥100
Number of counts - Motorway	D	-	≥100

(1) Pass if below the limit curve (Appendix 7a, Regulation EU 2018/1832)
(2) Pass if above the limit curve

Source: JRC.

Table 9. Subset of trip validity criteria and associated parameters.

Validity	Description
Trip characteristics group 1	Distance and share of urban rural and motorway parts
Trip characteristics group 2	Elevation absolute difference
	Total and urban cumulative positive elevation gain
Trip dynamics	Urban rural and motorway RPA; speed*acceleration, 95^{th} percentile
MAW	Share of urban, rural and motorway normal windows

Source: JRC.

5.2 Results

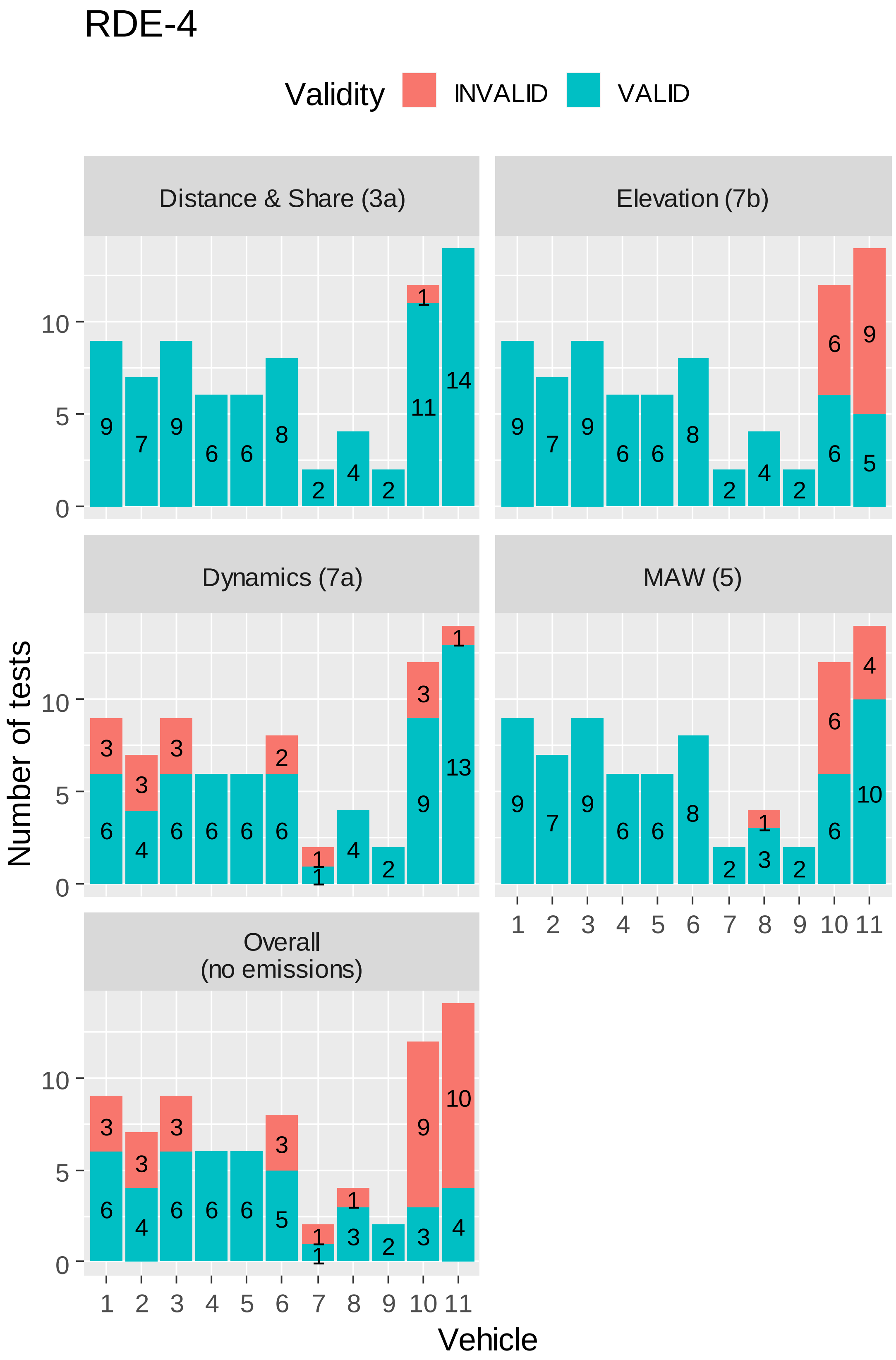
The criteria to assess the trip validity discussed in paragraph 5.1 were applied to the dataset by using EMROAD version 6.03. Figure 29 shows the number of valid/invalid tests depending on the criteria (panels) and vehicles. The number in the panel label refers to Appendix number of Regulation EU 2018/1832 and the "Overall" criterion represents the simultaneous validity of all criteria in Table 8; in summary:

- All tests but 1 fulfilled the requirements on trip characteristics in terms of covered distance and urban/rural/motorway share. This is related to the original trip design and does not depend on vehicles nor on driving;
- Vehicles 10 and 11 were tested in the European Alps with intentionally large altitude variations and consequent failures to comply with:
  - cumulative elevation gain requirements;
  - MAW requirements.
- Tests with intentional aggressive driving (see Table 6) exceeded the allowed trip dynamics;
- Vehicle 8, when tested in battery charge mode, produced larger amounts of CO_2 during the on-road trip and consequently did not comply with the MAW requirements.

EMROAD version 6.03 among other things allows the selection of the EU legislative framework of reference for data analysis, RDE-4 or RDE-3. The analysis above was thus repeated to compare the RDE-4 (upper panel) with the RDE-3 (lower panel) method in Figure 30. It is clear that the differences between the two methods are only related to the MAW trip validity criteria; all the other validity criteria remained unchanged (e.g. cumulative altitude gain, cold start operational requirements, trip shares). Detailed results per vehicle and criterion are given in Table 10 and Table 11 for RDE-4 and RDE-3, respectively, while Table 12 reports the difference of valid tests between RDE-4 and RDE-3, i.e. the number of valid RDE-4 tests which were invalid in RDE-3.

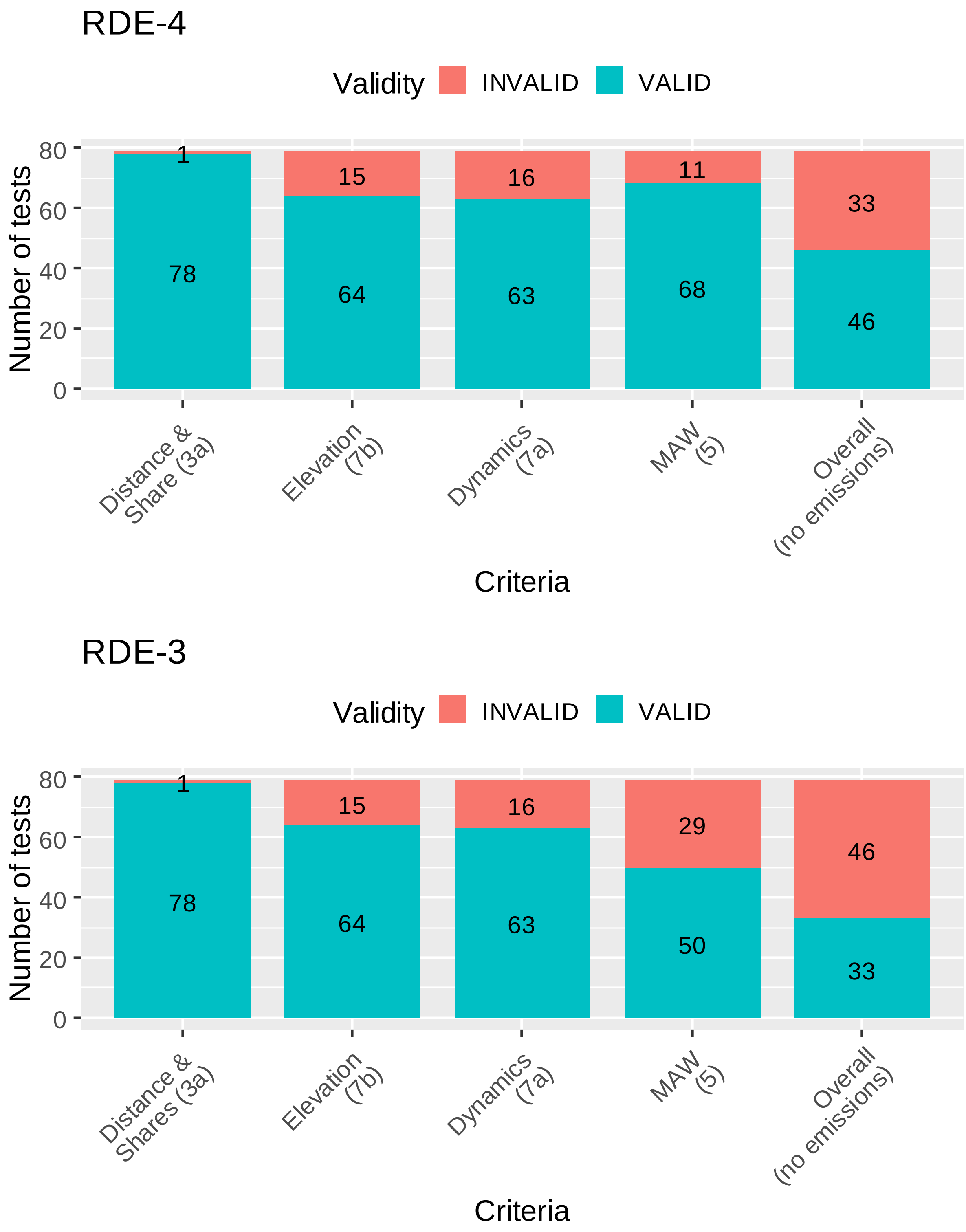
Figure 31 focuses on the MAW and displays the connections between valid/invalid tests and the legislative packages RDE-3 and RDE-4. It can be seen that all tests valid in RDE-3 remained valid in RDE-4 or alternatively, all invalid tests in RDE-4 were invalid in RDE-3 as well. In addition, there are 18 tests that changed their validity condition and passed from being invalid in RDE-3 to be valid in RDE-4. Therefore, the adjustments proposed in RDE-4 have widened the MAW boundary conditions.

Figure 29. Test validity per vehicle. Panels represent different validity criteria related to the appendix (number in parenthesis) of Regulation EU 2018/1832.



Source: JRC.

Figure 30. Test validity depending on chosen criteria: trip characteristics group 1 (distance and shares) and 2 (elevation gain), dynamics, MAW, and overall. See paragraph 5.1 for details.



Source: JRC

Table 10. Number of valid/invalid tests depending on validity criteria: trip characteristics, trip dynamics, moving averaging windows (MAW) and overall; see text for details. EMROAD version 6.03 according to RDE-4 package.

Criteria	RDE-4 Validity	Vehicles											
		1	2	3	4	5	6	7	8	9	10	11	All
Overall	INVALID	3	3	3	0	0	3	1	1	0	9	10	33
	VALID	6	4	6	6	6	5	1	3	2	3	4	46
Group 1	INVALID	0	0	0	0	0	0	0	0	0	1	0	1
	VALID	9	7	9	6	6	8	2	4	2	11	14	78
Group 2	INVALID	0	0	0	0	0	0	0	0	0	6	9	15
	VALID	9	7	9	6	6	8	2	4	2	6	5	64
Dynamics	INVALID	3	3	3	0	0	2	1	0	0	3	1	16
	VALID	6	4	6	6	6	6	1	4	2	9	13	63
MAW	INVALID	0	0	0	0	0	0	0	1	0	6	4	11
	VALID	9	7	9	6	6	8	2	3	2	6	10	68
Total tests		9	7	9	6	6	8	2	4	2	12	14	79

Source: JRC.

Table 11. Number of valid/invalid tests depending on chosen criteria: trip characteristics, trip dynamics, moving averaging windows (MAW) and overall; see text for details. EMROAD version 6.03 according to RDE-4 package. EMROAD version 6.03 according to RDE-3 package.

Criteria	RDE-3 Validity	Vehicles											
		1	2	3	4	5	6	7	8	9	10	11	All
Overall	INVALID	4	5	3	3	3	3	1	3	1	9	11	46
	VALID	5	2	6	3	3	5	1	1	1	3	3	33
Group 1	INVALID	0	0	0	0	0	0	0	0	0	1	0	1
	VALID	9	7	9	6	6	8	2	4	2	11	14	78
Group 2	INVALID	0	0	0	0	0	0	0	0	0	6	9	15
	VALID	9	7	9	6	6	8	2	4	2	6	5	64
Dynamics	INVALID	3	3	3	0	0	2	1	0	0	3	1	16
	VALID	6	4	6	6	6	6	1	4	2	9	13	63
MAW	INVALID	1	3	1	3	3	0	0	3	1	8	6	29
	VALID	8	4	8	3	3	8	2	1	1	4	8	50
Total tests		9	7	9	6	6	8	2	4	2	12	14	79

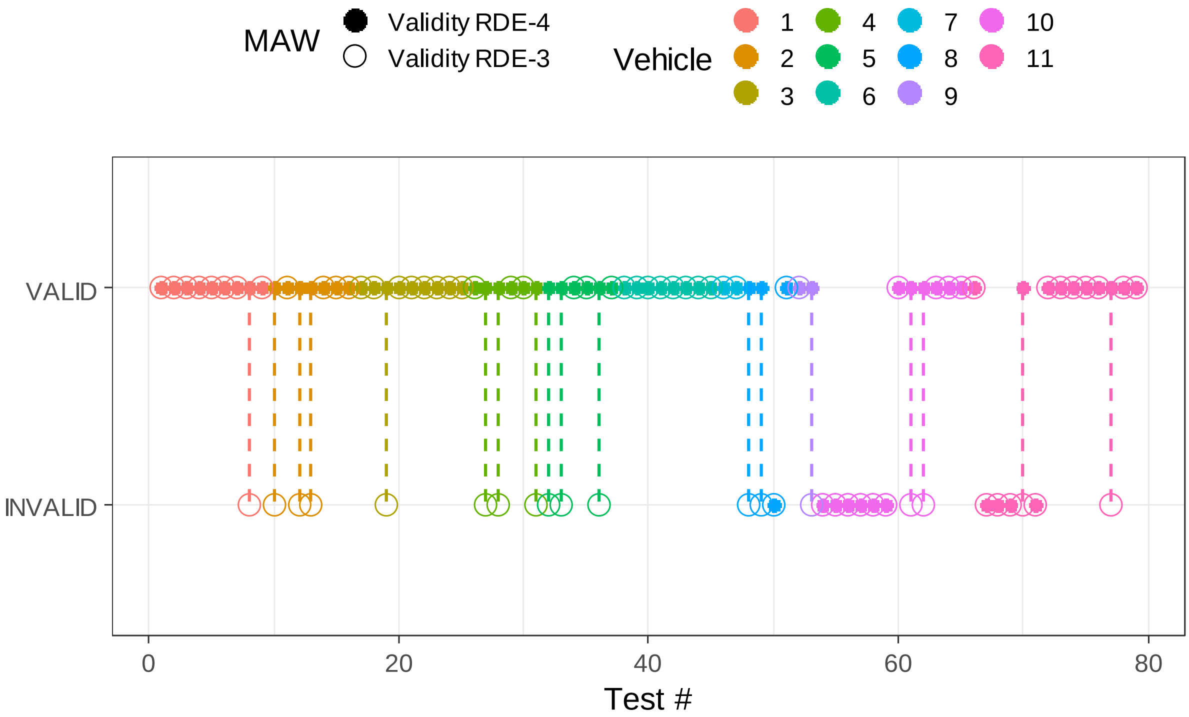
Source: JRC.

Table 12. Difference of valid tests between the RDE-4 and RDE-3 approaches.

Vehicle	1	2	3	4	5	6	7	8	9	10	11
Overall	1	2	0	3	3	0	0	2	1	0	1
Trip.char.1	0	0	0	0	0	0	0	0	0	0	0
Trip.char.2	0	0	0	0	0	0	0	0	0	0	0
Trip.dyn	0	0	0	0	0	0	0	0	0	0	0
MAW	1	3	1	3	3	0	0	2	1	2	2

Source: JRC.

Figure 31. Relation between MAW valid/invalid tests from RDE-4 and RDE-3 data treatments. Vertical lines connect tests which were invalid under the RDE-3 package and became valid under RDE-4.



Source: JRC.

6 Method for the final emissions calculation

6.1 Introduction

With the RDE-3 legislation (Annex IIIa, Regulation EU 2017/1151) and during the RDE reporting and monitoring phase (TNO, 2017), two methods were allowed both to check the trip validity and to calculate the final emissions for the test:

— The Moving Averaging Window method (MAW, in Appendix 5);

— The Power Binning Method (PBM, in Appendix 6).

After the analysis of the data collected during the reporting and monitoring phase, it became obvious that the emissions corrections included in both methods to compensate for the severity of the testing conditions were not properly correlated with the said severity. This absence of correlation has been primarily attributed to the mathematical rules present in both methods leading to undesired and excessive corrections of the emissions. Even for some "fully normal" tests (e.g. vehicle driven not aggressively, under moderate altitude and temperature conditions, with a low cumulative altitude gain), one could obtain final and corrected RDE emissions results very different from the ones measured over the total test without any correction.

It was generally recognized that the distance-specific CO_2 emissions were a good composite indicator to assess the driving severity, as it encompasses the effect of the driving dynamics, the payload, the road grade and the wind. As a consequence, it was decided:

— To keep the MAW method to assess the trip validity at an intermediate scale (the windows)

— To use the CO_2 of the trip (urban or total part) as the macroscopic indicator for the driving severity leading (or not) to an emissions correction.

6.2 Description of the emissions corrections

6.2.1 MAW weighing under RDE-3

The method is described in detail in Appendix 5 of Regulation EU 2017/1151. Here briefly, we focus on the calculations of emissions (as distance specific emissions over the complete RDE trip or its urban part) after an on-road trip with PEMS. The CO_2 characteristic curve is built upon the WLTP cycle including some multiplicative coefficients (disregarded in RDE-4) as follows:

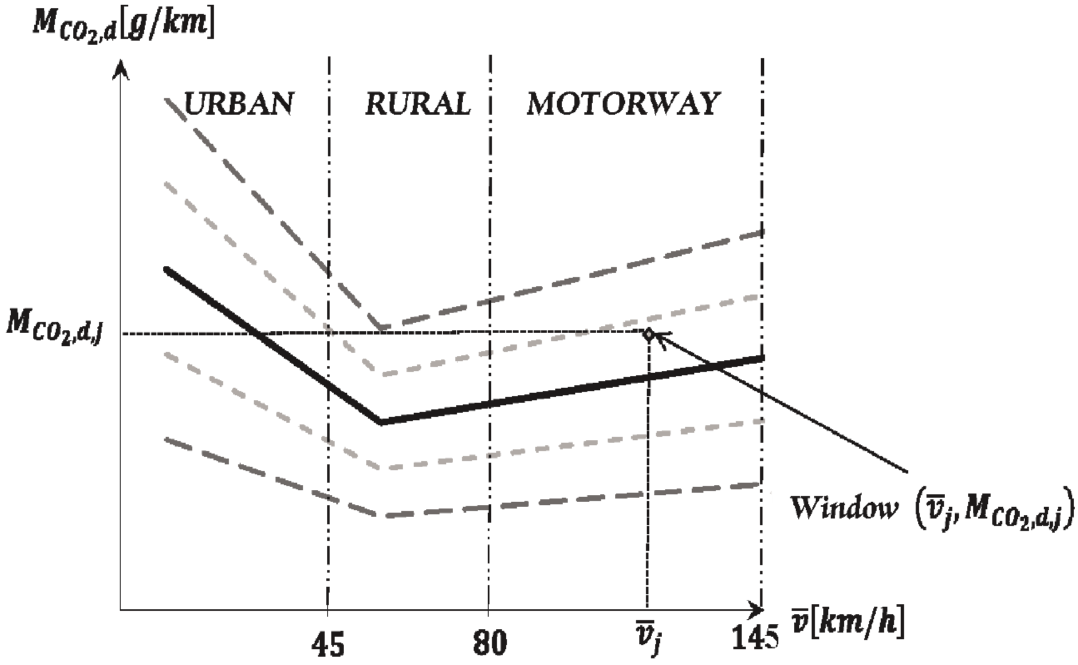
$M_{CO2,d,P1}$ = CO_2 emissions over the Low Speed phase of the WLTP cycle x 1,2 [g/km].

$M_{CO2,d,P2}$ = CO_2 emissions over the High Speed phase of the WLTP cycle x 1.1 [g/km]

$M_{CO2,d,P3}$ = CO_2 emissions over the Extra High Speed phase of the WLTP cycle x 1,05 [g/km]

The primary tolerance and the secondary tolerance of the CO_2 characteristic curve are respectively tol_1 = 25 % and tol_2 = 50 %, see Figure 32. Verification of test completeness (abandoned in RDE-4) and normality with respect to windows requires that the test include at least 15 % of urban, rural and motorway windows, out of the total number of windows. The test shall be normal when at least 50 % of the urban, rural and motorway windows are within the primary tolerance defined for the characteristic curve (compare with Table 8).

Figure 32. Vehicle CO_2 characteristic curve (solid black line) built over the WLTP cycle, and associated tolerances tol_1 (light grey, dashed) and tol_2 (dark grey, dashed). Subdivision of the window-speed domain in urban, rural and motorway windows is the same as in RDE-4.



Source: Regulation EU 2017/1151.

If the specified minimum requirement of 50% is not met, the upper positive tolerance tol_1 may be increased by steps of 1 percentage point until the 50% of normal windows target is reached. When using this approach, tol_1 shall never exceed 30%.

The emissions shall be calculated as a weighted average of the windows' distance-specific emissions separately for the urban, rural and motorway categories (u, r, m indices) and the complete trip (t index):

$$M_{gas,d,k} = \left(\frac{\sum w_j M_{gas,d,j}}{\sum w_j}\right)$$

with the weight w_j as function of a severity index h as in Figure 33:

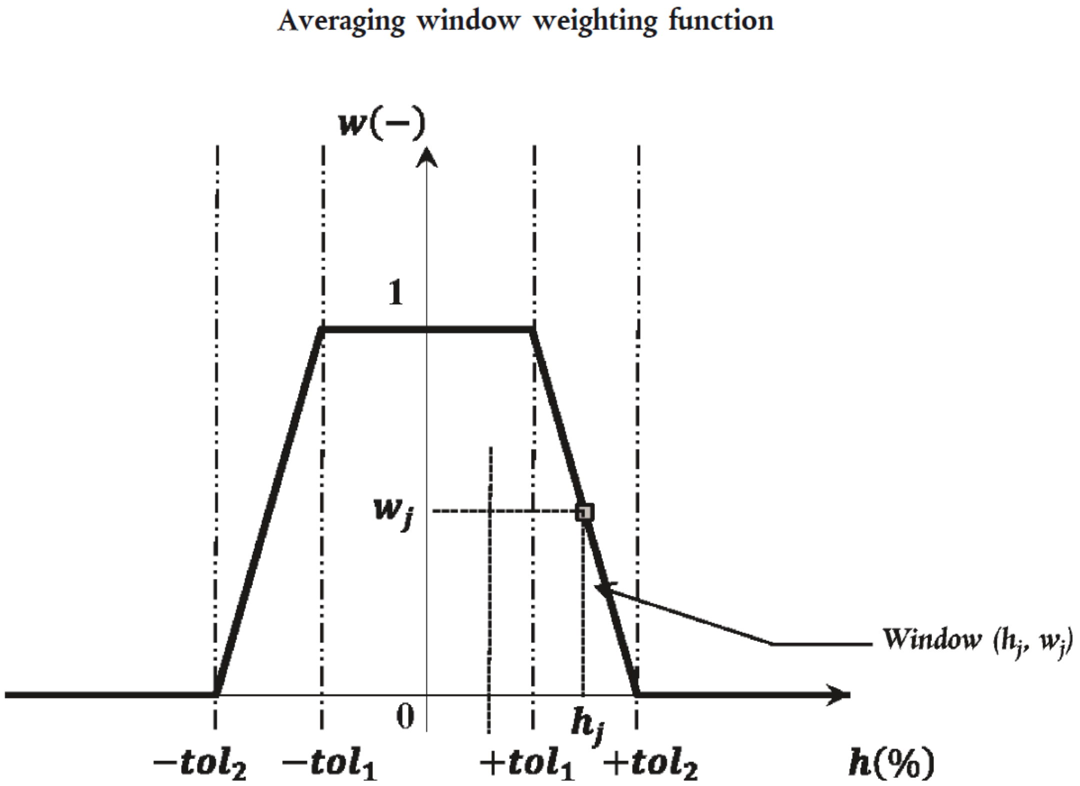
$$h_j = 100\ \frac{M_{CO2,j,d} - M_{CO2,d,CC}(v_j)}{M_{CO2,d,CC}(v_j)}$$

$$\bar{h}_k = \frac{1}{N_k}\sum h_j\,, \qquad with\ k = u, r, m$$

$$\bar{h}_t = \frac{f_u\bar{h}_u + f_r\bar{h}_r + f_m\bar{h}_m}{f_u + f_r + f_m}$$

where $f_u = 0.34$ and $f_r = f_m = 0.33$.

Figure 33. Weighting of the MAW as a function of the severity index. This methodology is no longer present in RDE-4.



Source: Regulation EU 2017/1151.

6.2.2 CO_2-based correction under RDE-4

For the valid trips, the final RDE results $M_{RDE,k}$ are calculated with a multiplicative evaluation factor RF_k. For the complete RDE trip and for the urban part of the RDE trip

$$M_{RDE,k} = m_{RDE,k} * RF_k$$

where k=t=total or k=u=urban, $m_{RDE,k}$ is the distance-specific mass of gaseous pollutant [mg/km] or particle number [#/km] emissions emitted over the RDE trip (total or urban), RF_k is the results evaluation factor expressed as a function of the ratio r_k between the CO_2 emissions measured during the RDE test and the WLTP test:

$$r_k = M_{CO2,RDE,k}/M_{CO2,WLTP}$$

The results evaluation factor is described in Table 13. (Table App 6.1 of Regulation EU 2018/1832). The parameter RF_{L1} and RF_{L2} of the function used to calculate the result evaluation factor are as follows:

Upon the request of the manufacturer and only for type approvals granted before 1 January 2020:

RF_{L1} = 1,20 and RF_{L2} = 1,25;

in all other cases:

RF_{L1} = 1,30 and RF_{L2} = 1,50;

Table 13. Result evaluation factor description and values.

When	RF_k	Where
$r_k \leq RF_{L1}$	$RF_k = 1$	
$RF_{L1} < r_k \leq RF_{L2}$	$RF_k = a_1 r_k + b_1$	$a_1=(RF_{L2}-1)/[RF_{L2}*(RF_{L1}-RF_{L2})$ $b_1=1-a_1RF_{L1}$
$r_k > RF_{L2}$	$RF_k=1/r_k$	

Source: Regulation EU 2018/1832.

For the urban emissions (k=u), the relevant phases of the WLTP driving cycle shall be:

— For ICE vehicles the first two WLTP phases, i.e. the Low and the Medium speed phases;

— For non-off-vehicle-charge (non-plug-in) hybrid electric vehicles (NOVC-HEVs) the whole WLTP driving cycle.

For off-vehicle-charge (plug-in) OVC-HEV the distance-specific CO_2 over the WLTP test is obtained with the vehicle in Charge Sustaining mode. In either urban or total part of the trip:

$$r_k = \left(\frac{M_{CO2,RDE,k}}{M_{CO2,WLTP,CS,k}}\right) * \left(\frac{0.85}{IC_k}\right)$$

where IC_k is the ratio of the distance driven either in urban or total trip with the combustion engine on divided by the total urban or total trip distance:

$$IC_k = \frac{d_{ICE,k}}{d_{ICE,k} + d_{EV,k}}$$

6.3 Effect of the RDE-3/RDE-4 emissions corrections

The emission correction methods based on CO_2 according to the RDE-3 and RDE-4 legislative packages (Regulation EU 2017/1151, Regulation EU 2017/1154, Regulation EU 2018/1832) where applied to our dataset for comparison.

Figure 34 and Figure 35 summarize the relation between the ratio r_k = *RDE* CO_2 */WLTC* CO_2 and the result evaluation factor RF_k (in the RDE-3 and RDE-4 formulations) for the total and urban parts of the trip, and for all tests or only valid tests.

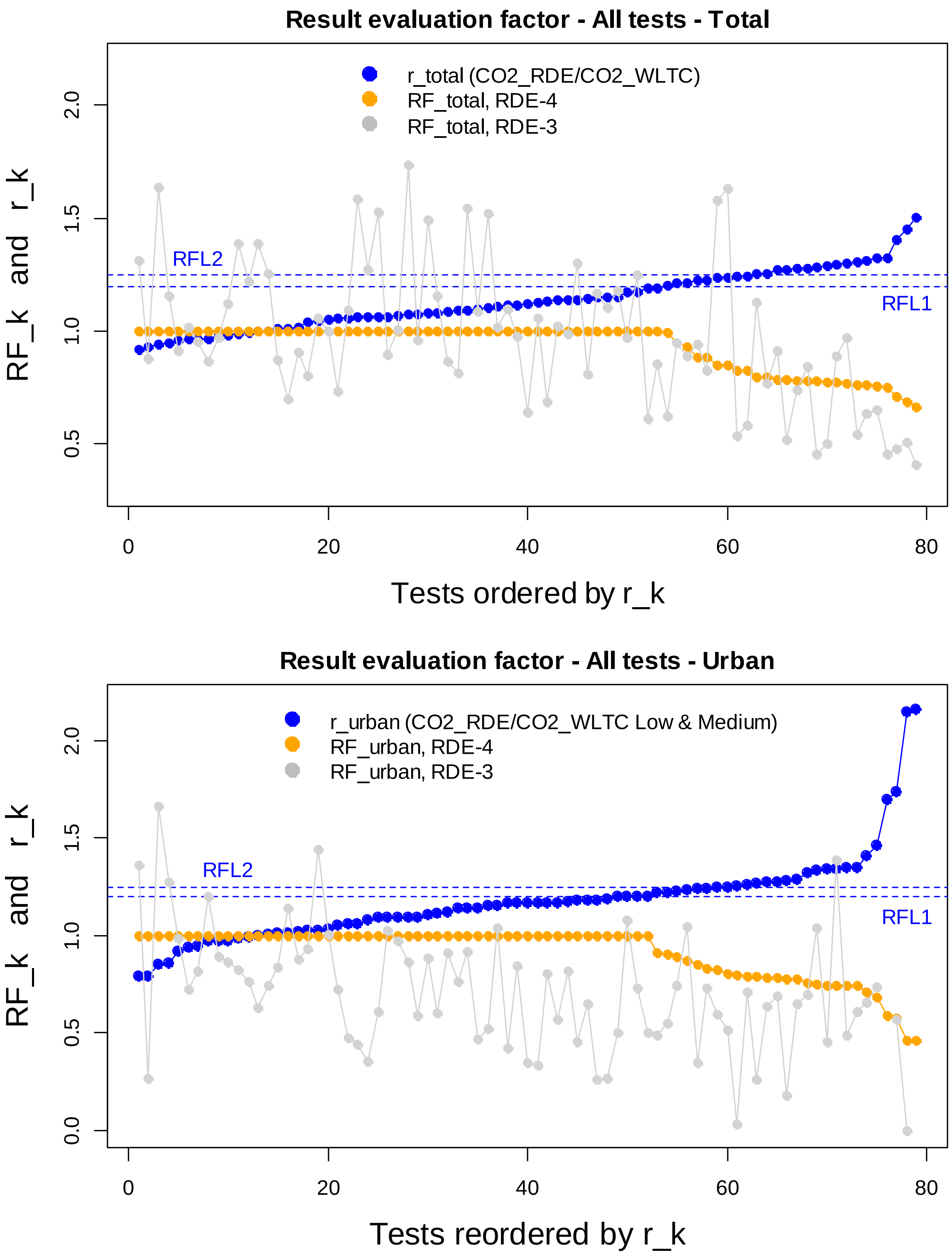
The grey line, representing the correction in the RDE-3 regulation, shows the absence of correlation between the emissions correction by the RDE-3 MAW method and the r_k values. For r_k values up to approximately 1.2, the emissions corrections were either positive or negative and exhibited a strongly varying magnitude. For r_k values above 1.2, there was a trend towards a correction reducing the emissions.

The emissions correction strategy introduced in RDE-4 links the emissions corrections with the r_k values in a more systematic and transparent manner, as evidenced by the orange curve: no correction (i.e. real RDE trip distance-specific emissions) up to a certain value of r_k (1.2 in the first regulatory stage), and then an increase of the correction following the increase of RDE CO_2 emissions. RF_k in RDE-4 is more stable than in RDE-3 because RF_k in RDE-4 is governed by r_k and RF_L parameters, while the RF_k for RDE-3 was calculated ex-post with NOx RDE final / NOx PEMS raw data

It is informative to summarize the cumulative correction applied to raw emissions measured with PEMS during an RDE trip. In fact, the result evaluation factor investigated above is applied to data after the correction for extended conditions (see chapter 3), if applicable. The combined contribution of the two corrections is displayed in Figure 36 and

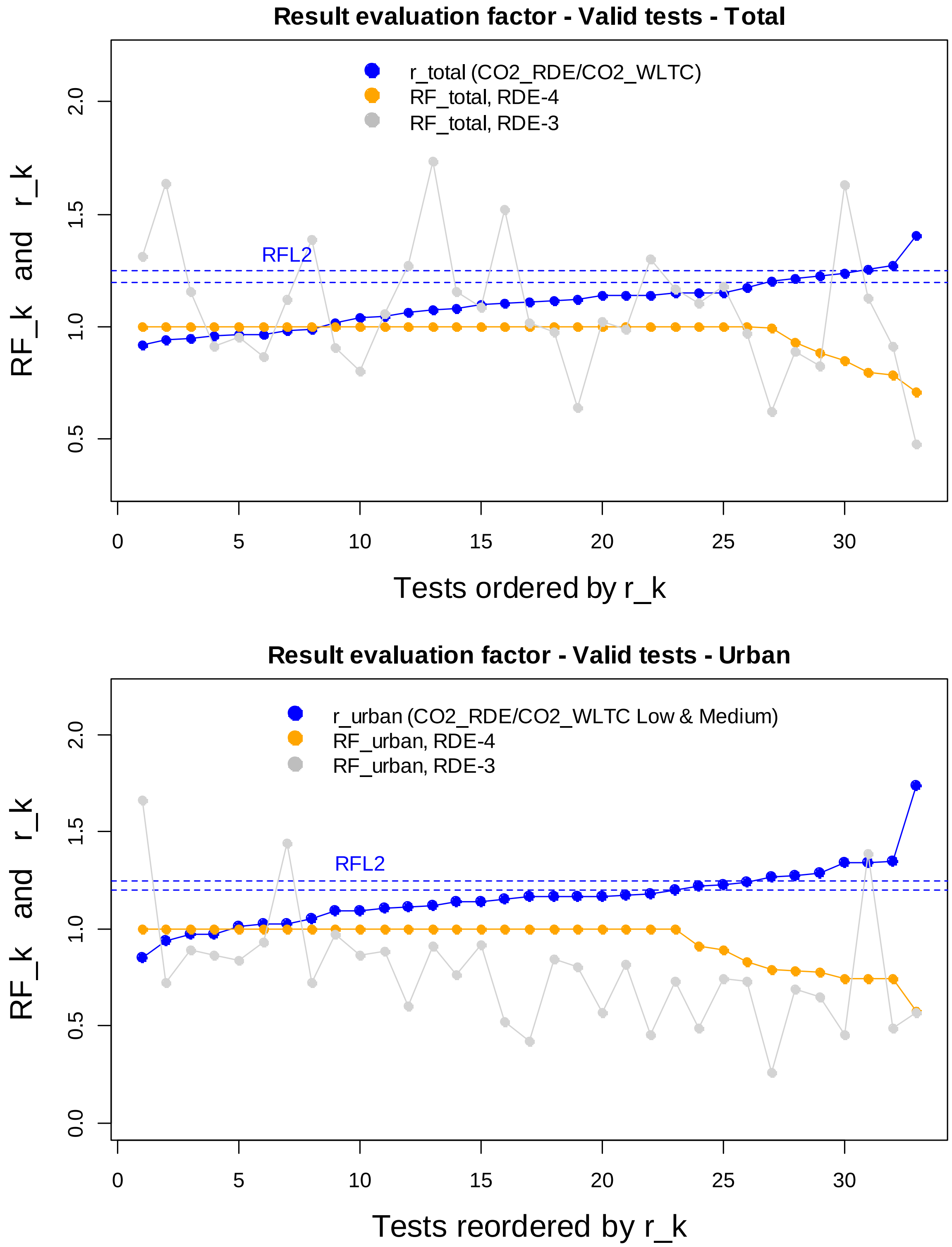
Figure 37 for all tests and valid tests, respectively, and for the total and urban part of the trip. The percentage of data affected by the extended conditions correction is also reported.

Figure 34. Result evaluation factor for the 79 RDE trips evaluated with EMROAD version 6.03, under the RDE-4 and RDE-3 packages. The entire test was considered (k=total). RF_{L1} and RF_{L2} are valid until 01/01/2020.



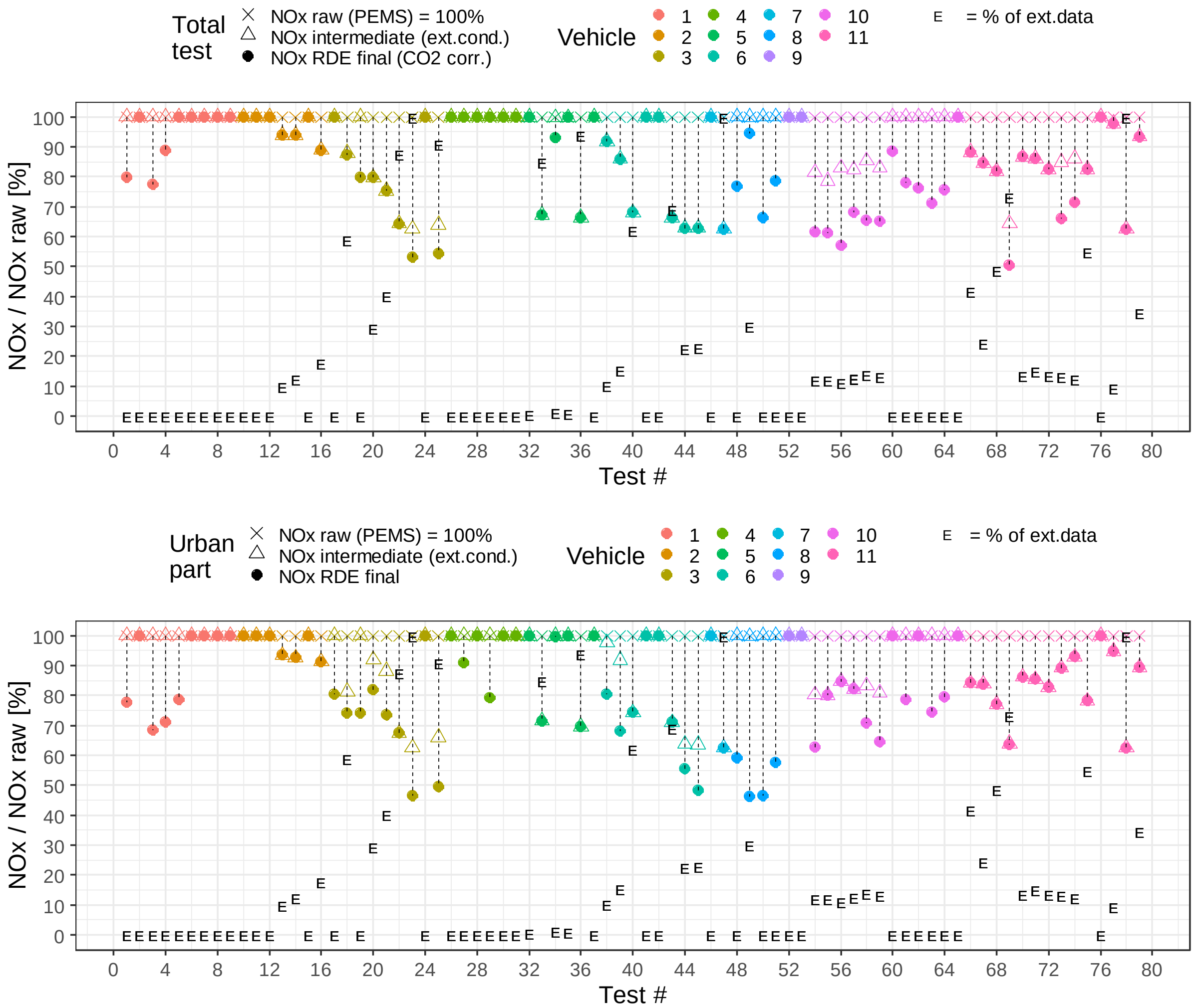
Source: JRC.

Figure 35. Result evaluation factor for the overall valid 34 trips evaluated with EMROAD version 6.03, under the RDE-4 and RDE-3 packages. The entire test was considered (k=total). RF_{L1} and RF_{L2} are valid until 01/01/2020.



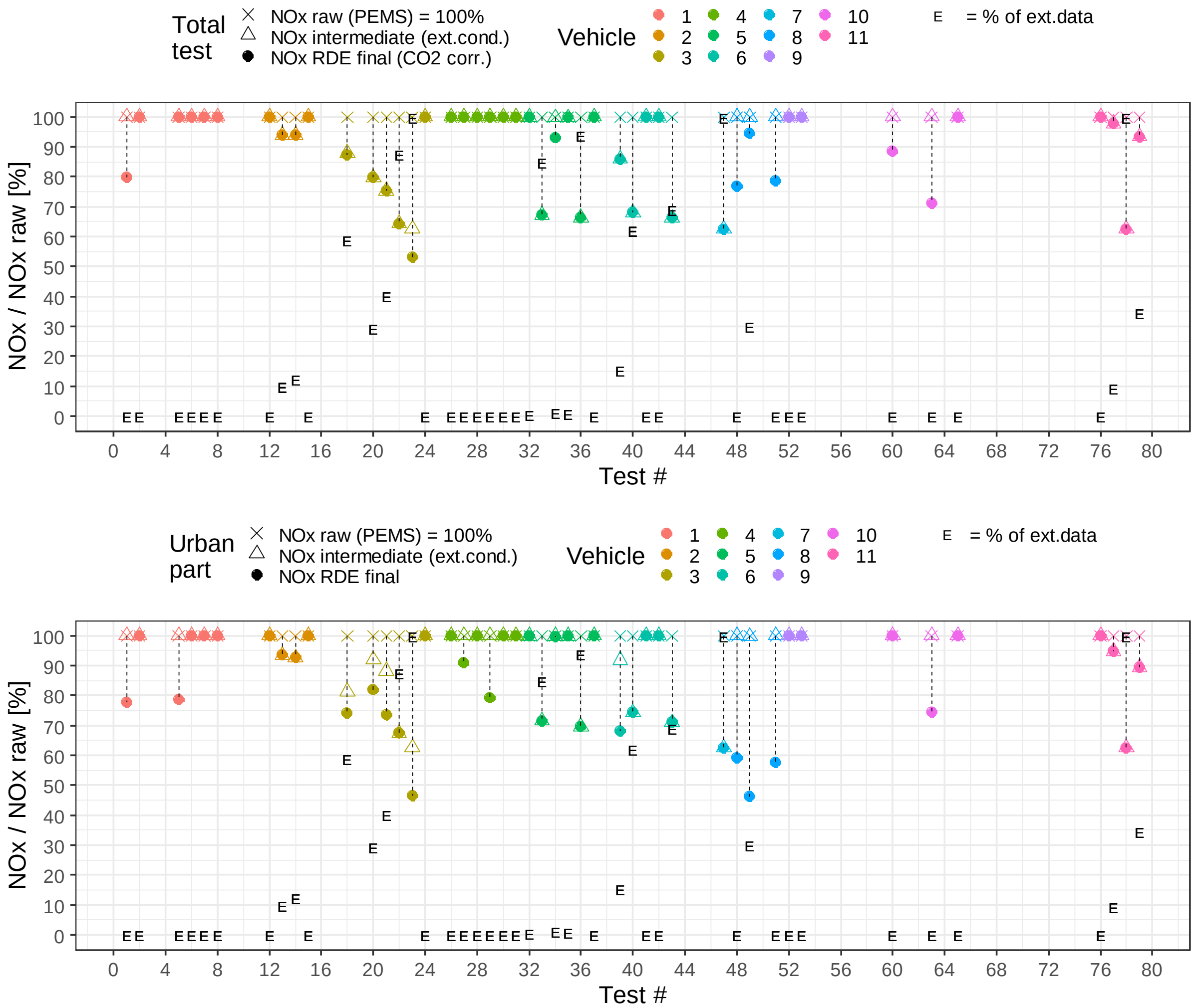
Source: JRC.

Figure 36. Cumulative emission correction of the raw data (100% = before correction): extended conditions correction (intermediate) and correction due to CO_2 (final) for all tests. Total trip and urban part in upper and lower panels, respectively. "E" is the percentage of extended condition data, i.e. the amount of data to which the first of the two corrections is applicable.



Source: JRC.

Figure 37. Cumulative emission correction of the raw data (100% = before correction): extended conditions correction (intermediate) and correction due to CO_2 (final) for valid tests only. Total trip and urban part in upper and lower panels, respectively. "E" is the percentage of extended condition data, i.e. the amount of data to which the first correction is applicable.



Source: JRC.

7 Conclusions

This Technical Report describes specific elements of the European Union Real-Driving Emission (EU-RDE) legislation (3rd and 4th packages) in support of the working group at the United Nations (RDE-IWG) ([9]) in charge of drafting harmonized technical regulations on RDE. The most recent available version of the in-house developed EMROAD software tool ([10]) (version 6.03) was used to analyse a dataset consisting of 11 vehicles tested over 79 RDE trips with focus on the CO_2 characteristic curve, its tolerances, and applicable CO_2–based corrections in RDE package 4 compared to package 3.

From the introduction of the Euro 1 standard in 1992 ([11]) to the latest amendments to the Euro 6 standard ([12]), the procedures to test the environmental performance of road vehicles such as passenger cars have been routinely updated in accordance with the technological developments. Relevant to this Report, the EU introduced mandatory RDE tests in several steps starting from 2016 as a result of experimental studies and monitoring phases (Weiss et al. 2011; 2013; TNO 2017).

The main chronological steps of the EU-RDE legislation were as follows:

— May 2015, adoption of the 1st RDE package (RDE-1, Regulation EU 2016/427): Test procedures, instrumentation requirements, evaluation method;

— October 2015, adoption of the 2nd RDE package (RDE-2, Regulation EU 2016/646): boundary conditions, NOx conformity factor ([13]), introduction timing;

— December 2016, adoption of the 3rd RDE package (RDE-3, Regulation EU 2017/1154): PEMS PN with conformity factor, cold engine conditions at test start;

— May 2018, adoption of the 4th RDE package (RDE-4, Regulation EU 2018/1832): RDE testing for in-service conformity and market surveillance.

A temporary conformity factor CF=2.1 for NOx (valid from 2017 to 2021) was introduced to allow manufacturers to adapt to the RDE requirements until replacement with a final CF=1.43 for NOx and CF=1.5 for PN.

The aforementioned legislation sets the following timeline for the European passenger car fleet:

— From April 2016: Euro 6c. RDE testing complementary to the regulatory test-cycle for new Euro 6 passenger car models. Emissions should be measured with Portable Emissions Measurement System (PEMS) only for monitoring purposes and no emission limit value is applicable;

— From September 2017: Euro 6d-temp. A NOx and PN not-to-exceed limit NET = Euro 6 limit * $CF_{temporary}$ is set for new car models (all new cars from September 2019);

— From January 2020/21: Euro 6d. RDE testing against final CFs is applied.

The RDE procedures include main elements such as the boundary conditions (under which the tests have to be conducted), the instrumentation minimum performance requirements and the test protocol. Early choices were made to assess the vehicles RDE performance for urban driving and for a mix of urban/rural/motorway driving on a single trip.

The present work focuses on the fine tuning of 2 major elements:

([9]) Global Real Driving Informal Working Group (GRDE), Working Party on Pollution and Energy (GRPE), World Forum for Harmonization of Vehicle Regulations (WP.29), United Nations Economic Commission for Europe (UNECE). See https://wiki.unece.org/pages/viewpage.action?pageId=63308214.
([10]) https://circabc.europa.eu
([11]) Directive 91/441/EEC
([12]) Regulation EU 2017/1151
([13]) A multiplicative conformity factor applied to the Euro 6 limit value takes into account the additional measurement uncertainties introduced by the PEMS equipment.

- The definition of the boundary conditions for the driving dynamics assessed using the MAW CO_2 emissions, in relation with the vehicle CO_2 emissions on a reference test cycle (WLTP);
- The calculation of the final emissions value(s) for the RDE trip, with a view to their use for decision making in a regulatory context.

The main challenge was to propose a robust data evaluation method, able to determine whether a test is driven under the selected driving dynamics boundaries and to report realistic on-road vehicle emissions, introducing corrections only for the trips (or parts of the trips) which are considered as more severe in terms of ambient temperature/altitude and driving behaviour. Clearly, such evaluation can only be conducted ex-post, due to uncontrolled factors that can be encountered during an RDE trip (traffic, weather and to some extent driver's habits). The initial idea to use the intermediate scale of the windows (in the RDE-3 package, see section 6.2.1) to introduce these corrections was not entirely successful. The proposed improvements of Regulation 2018/1832 leads to transparent results: real emissions of the vehicle on an RDE trip. The settings proposed for the boundary conditions might be adjusted later according to the regulatory needs.

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Platt et al., 2014, *Two-stroke scooters are a dominant source of air pollution in many cities*, NATURE COMMUNICATIONS, 5:3749, DOI:10.1038/ncomms4749.

Regulation (EC) 715/2007 of the European Parliament and of the Council of 20 June 2007 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. OJ L 171, 29.06.2007, p. 1-16.

Regulation (EC) 692/2008 of 18 July 2008 implementing and amending 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. OJ L 199, 28.07.2008, p. 1-136.

Regulation (EU) 2016/427 of 10 March 2016 amending Regulation (EC) No 692/2008 as regards emissions from light passenger and commercial vehicles (Euro 6). OJ L 82, 31.3.2016, p. 1-98.

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List of abbreviations and definitions

CF Conformity Factor

CH_4 Methane

CI Compressed ignition

CO Carbon monoxide

CO_2 Carbon dioxide

DG-GROW Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs

DOC Diesel oxidation catalyst

EC European Commission

EC-JRC European Commission – Joint Research Centre,

EFM Exhaust Flow Meter

EU European Union

EU-RDE European Union Real Driving Emissions

HC Hydrocarbons

IWG Informal Working Group (at United Nations)

JRC Joint Research Centre, at the European Commission

LNT Lean-NOx trap

MAW Moving Average Windows

$M_{CO2,RDE,k}$ Distance-specific mass of CO_2 [g/km] over the RDE trip

$M_{CO2,WLTC}$ Distance-specific mass of CO_2 [g/km] over the WLTP cycle

$M_{CO2,WLTC\_CS,k}$ Distance-specific mass of CO_2 [g/km] over the WLTP cycle for an OVC-HEV vehicle tested on its charge sustaining mode

$M_{CO2,d,CC}$ Distance-specific mass of CO_2 [g/km] of the vehicle CO_2 characteristic curve

$M_{CO2,ref}$ Reference CO_2 mass (kg) over the WLTP

NEDC New European Driving Cycle

NOVC-HEV Not off-vehicle charging hybrid electric vehicle

NO Nitrogen monoxide

NO_2 Nitrogen dioxide

NOx Oxides of Nitrogen

OVC-HEV Off-vehicle charging hybrid electric vehicle

O_2 Oxygen

PEMS Portable Emission Measurement System

PM Particle Mass

PMP Particle Measurement Programme

PN Particle Number

RDE Real Driving Emissions

RDE-IWG Real Driving Emissions - Informal Working Group (at United Nations)

RF_k Result evaluation factor for the RDE trip.

RF_{L1}, RF_{L2} First and second parameters of the function used to calculate the result evaluation factor

r_k ratio between the CO_2 emissions measured during the RDE test and the WLTP test

RPA Relative Positive Acceleration

SI Spark-ignition

SCR Selective Catalytic Reduction

STU Sustainable Transport Unit (at JRC)

THC Total hydrocarbons

tol_{1H}, tol_{1L} Upper and lower tolerances around the vehicle CO_2 characteristic curve

TWC Three-way Catalyst

UN United Nations

UNECE United Nations Economic Commission for Europe

VELA Vehicles Emissions Laboratories of the European Commission (at JRC)

WLTC Worldwide-harmonized Light duty vehicles Test Cycle

WLTP Worldwide-harmonized Light duty vehicles Test Procedure

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