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Comparison of the Real-Driving Emissions (RDE) of a Gasoline Direct Injection (GDI) Vehicle at Different Routes in Europe

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Abstract: On-road real-driving emissions (RDE) tests with portable emissions measurement systems (PEMS) are part of the vehicle emissions regulations in the European Union (EU). For a given vehicle, the final emission results depend on the influence of the ambient conditions and the trip characteristics (including the driver's behaviour) on the vehicle performance and the instrument measurement uncertainty. However, there are not many studies that have examined the emissions variability of a single vehicle following different routes. In this study, a 1.2 L gasoline direct injection (GDI) Euro 5b passenger car without a particulate filter and a PEMS was circulated in seven European laboratories. At their premises, the laboratories performed two to five repetitions of on-road trips compliant with the EU RDE regulation. The ambient temperature ranged between 7 °C and 23 °C. The average emission levels of the vehicle were 135 g/km for CO_2, 77 mg/km for CO, 55 mg/km for NO_x, and 9.2×10^{11} #/km for particle number. The coefficient of variance in the emissions following the same route was 2.9% for CO_2, 23.8% for CO, 23.0% for NO_x, and 5.8% for particle number. The coefficient of variance in the emissions following different routes in Europe was 6.9% for CO_2, 9.1% for CO, 0.0% for NO_x, and 9.1% for particle number. The previous values include the specific vehicle emissions variability under the narrow test conditions of this study, but only partly the PEMS measurement uncertainty because the same instrument was used in all the trips. The results of this study can be used by laboratories conducting RDE tests to assess their uncertainty budget when testing or comparing vehicles of similar technology.

Keywords: vehicle emissions; on-road emissions; real-driving emissions (RDE); portable emissions measurement systems (PEMS); CO_2; NO_x; particle number

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1. Introduction

Measuring vehicle emissions on the road is becoming more and more common [1–10]. On the one hand, a lot of research is conducted to determine the realistic behaviour or emission factors of light-duty and heavy-duty vehicles [11–17]. On the other hand, most regulations worldwide require emissions compliance to the limits not only in the laboratory but also on the road under normal conditions of use [18]. The on-road testing for regulatory purposes started in the United States of America (USA) in 2007 for heavy-duty vehicles. Europe introduced Portable Emissions Measurement Systems (PEMS) testing a few years later (in 2013) for heavy-duty vehicles with Regulation (EU) 582/2011 [19] and for light-duty vehicles (in 2017) with Real-Driving Emissions (RDE) Regulation (EU) 2016/427 [20]. Since then, various regulations have improved the procedures [21–24] and were included in the Euro 6 regulation [25]. Table 1 summarises some of the key additions in the light-duty RDE regulation, sometimes called first to fifth RDE packages. The first two packages were consolidated in the worldwide harmonised light-vehicle test procedure (WLTP) Regulation (EU) 2017/1151 [25], which was further developed by the third and fourth packages.

Euro 6d-t entered into force in September 2017, Euro 6d in September 2020, and Euro 6e in September 2023 (January 2025 for Euro 6ebis). In Asia, China introduced on-road provisions with China 6b in 2023 and India with Bharat Stage 6 Phase II in 2023 [18,26].

Table 1. Overview of key RDE EU regulations additions.

Regulation	Euro	M_{NOx}	M_{PN}	Drift	Driving Dynamics	Other Changes
2016/427 [20]	6c	-	-	$NO \leq 5$ ppm $NO_2 \leq 5$ ppm	-	RDE for type approval
2016/646 [21]	6d-t 6d	1.10 0.50	- -	Same	RPA, $v \times a$ CPEG	
2017/1154 [22]	6d-t	same	0.50	$NO_x \leq 5$ ppm	same	Cold start inclusion; order urban, rural, motorway; hybrids; regeneration
2018/1832 [23]	6d	0.43	same	Same	same	RDE also for ISC and surveillance; simplified evaluation method; EFM should cover 75% FS
2023/443 [24]	6e	0.10	0.34	$NO_x \leq 3$ ppm	same	$T_{max,extended}$ 38 °C (Euro 6ebis) (from 35 °C); stricter vehicle conditioning test for cold start test; soaking up to 72 h (from 56), drift correction

CPEG = cumulative positive elevation gain; EFM = exhaust flow meter; EU = European Union; M = margin; FS = full scale; RDE = real driving emissions; RPA = relative positive acceleration.

Although on-road testing is more representative of the reality than laboratory testing, the results might exhibit higher scatter due to the variable vehicle response and usage and the wider ranges of possible ambient and driving conditions, even when keeping all possible influencing parameters constant (e.g., fuel, pre-conditioning, weight (payload), use of air-conditioning, and other auxiliaries, etc.) [27]. The variability of emissions measured over different routes is caused by a composite of (i) the stability of the engine and the aftertreatment devices under identical conditions, (ii) the influence of the ambient conditions on the vehicle emissions performance (including parameters such as temperature, wind, road quality), (iii) the influence of the trip characteristics (e.g., driving style, route composition, traffic conditions, etc.) on the vehicle emissions performance, and (iv) the instrument accuracy and stability. The European regulation requires that light-duty vehicles respect the NO_x and particle number (PN) Euro 6 emission limits under the normal driving conditions defined by the RDE regulation; i.e., the potential variability of the emissions caused by points (i) to (iii) are included. The intention of the regulators is to avoid poor performance of the emissions control technology (e.g., efficient only under certain conditions) and to capture the exceedance of the regulated limits if and when this happens. Within the regulated conditions, voluntary strategies (Auxiliary Emissions Strategies) are permitted. Outside the regulated conditions, auxiliary strategies may be permitted under certain conditions aiming to protect the engine and the aftertreatment against damage or accident and for the safe operation of the vehicle [28]. These conditions are assessed by the responsible type approval authority, in particular, if their effect on the emissions can be justified and quantified [29,30].

It is important to avoid cases in which a vehicle would be falsely considered to exceed the emission limits due to the instrument measurement inaccuracy; i.e., point (iv) should be taken into account in the emission compliance assessment. For this reason, the maximum PEMS measurement uncertainty that can occur during all potential RDE testing conditions is taken into account in the EU regulation as a "margin" on top of the regulated emission limits (NO_x and PN), applicable to all vehicles (with direct injection engines for PN) and regulated testing conditions [31,32]. A novelty of the Euro 6e is that the "margin" is now included in the final RDE results and not on the limit (Appendix 11, Annex III of Regulation (EU) 2023/443 [24]). Consequently, the same limit applies to testing in the laboratory and on the road. The term "conformity factor" (1+margin) referring to permissible exceedance of the laboratory limits on the road is not used anymore, but only "margin". The approach of

Euro 6e will also be followed in Euro 7 [33]. In the USA, both the measurement uncertainty and the differences between laboratory engine and on-road vehicle testing are taken into account in the not-to-exceed limit [34].

On the one hand, a wide range of conditions (driving style, ambient temperature, altitude, vehicle payload, i.e., "boundary conditions" according to the regulation) is desirable to assess the compliance of a car. On the other hand, similar conditions are desirable when the aim is to compare the emissions of different vehicles or have an indication of the laboratory's repeatability for certification purposes. Repeatability is the precision (i.e., closeness) of measurements of the same or similar objects at the same location with the same measurement procedure, system, operator, and operating conditions over a short period of time. Reproducibility, on the other hand, is the precision of measurements of the same or similar objects but at different locations, with different measuring systems and operators and over a longer period of time. While the definitions are straightforward for laboratory testing, for on-road RDE testing, the terms cannot be strictly used because it is almost impossible to have identical conditions on two trips at the same or at different locations (local traffic and weather conditions cannot be controlled, for instance) [35]. Furthermore, the inherent variability of the vehicle response is included and cannot be avoided. Under strict laboratory conditions, this variability can be small, but during the on-road testing, the environmental conditions and the trip characteristics are not well-controlled and might result in high vehicle emissions variability. Only a few studies have examined the variability of results following the same route and trying to keep all parameters similar [36,37]. A few researchers examined different routes with different trip characteristics [38–40]. To our knowledge, there are no studies that have compared the emissions and the characteristics of different RDE trips for the same vehicle and the same PEMS at different locations. As the studies regarding the influence of the trip on the results are limited, there is a need to better understand the variability of the emissions due to different trip characteristics, in particular, those compliant with the EU RDE regulation, which, in principle, is the same with China's, India's, and United Nations' Regulation 168 [41].

This study addresses the trip-to-trip variability over different RDE trips compliant with the EU requirements. In particular, the variability of the RDE testing procedure is assessed under similar (i.e., narrow range of) environmental and driving conditions using the same vehicle and the same measurement equipment at different locations in Europe. According to our knowledge, no other similar studies have been conducted before. The results of this study can be a first input of expected differences due to different trip characteristics for both regulators and researchers. It has to be highlighted that this study does not assess the possible variation in the PEMS response (measurement uncertainty), which has been thoroughly assessed in other studies [32,42,43]. As many changes took place in the RDE regulation over the years, the text also gives some historical information regarding the evolution of the RDE technical specifications.

2. Materials and Methods

The objective of the original inter-laboratory comparison exercise was to assess the measurement performance of particle number (PN) PEMS. This exercise directly involved the regulators, the industry, and the technical services. For this reason, a PEMS (i.e., gas analyzers, PN analyzer, exhaust flow meter, GPS, and weather station and batteries) and two additional PN-PEMS were installed in a reference ("Golden") vehicle and were tested in different laboratories and their premises across Europe [44]. The original report assessed the measurement performance of the two additional PN-PEMS by comparing them to the laboratory reference systems on chassis dynamometers and to each other.

In this study, we evaluate the PEMS data (gases and particles) that were not analyzed in the previous report, as they were outside of the scope of the exercise. Furthermore, the approach is different. Here, we focus on the variability of the on-road tests for gases and particles, while in the original report, only relative differences in PN-PEMS to the reference laboratory systems were assessed. Using the results from the same PEMS applied in different laboratories allows for expressing the variability of the emissions on the same or different routes without taking into account the bias and uncertainty related to the use of different PEMS. The results of the two additional PN-PEMS and their measurement uncertainty can be found in the original report [44]. The details of the exercise can be found in the report as well, so here, only the most relevant information for understanding this study is summarised. The on-road tests took place at the end of 2015 at the premises of the following European laboratories in this chronological order:

- Lab #1: JRC (Joint Research Centre), Ispra, Italy (mid-September);
- Lab #2: Volkswagen, Wolfsburg, Germany (end of September);
- Lab #3: Bosmal (Automotive R&D institute), Bielsko-Biala, Poland (beginning of October);
- Lab #4: Honda R&D Europe, Offenbach am Main, Germany (end of October);
- Lab #5: Audi, Neckarsulm, Germany (beginning of November);
- Lab #6: Volvo, Gothenburg, Sweden (end of November);
- Lab #7: TÜV Nord, Essen, Germany (beginning of December);
- Lab #1 repeated at the end of the exercise (end of December) in order to confirm the stability and the absence of drift of the emissions.

Although the tests were performed 2 years before RDE's introduction to the regulation and 8 years before the last package, they still have high interest and value as no such study has been conducted since then. Furthermore, the next Euro 7 step has kept the same (or similar) testing methodology (RDE) and technical specifications for the instruments.

The vehicle was a C-segment Volkswagen Golf, with 1.2 L gasoline direct injection (GDI) with a three-way catalyst (but no particulate filter), with maximum power of 63 kW, manual gearbox, kerb weight of 1205 kg, maximum laden mass of 1720 kg, and 9800 km on the odometer. The equipment installed in the car was a PEMS (for gases and PN) and two additional PN-PEMS. It was type-approved as a Euro 5b vehicle (model year 2015), and thus, no emission limits were applicable for RDE testing, as the RDE procedure was not in the regulation at that time.

The PEMS was the Semtech LDV from Sensors (Saline, MI, USA) measuring CO and CO_2 with non-dispersive infrared detectors, NO and NO_2 with non-dispersive ultraviolet detectors, and (solid) PN with condensation particle counter with thermal pretreatment [31]. A 1.5-inch Exhaust Flow Meter (EFM) was used (maximum exhaust flow around 250 kg/h). It also logged the position coordinates, altitude, as well as ambient temperature, pressure, and relative humidity. The PEMS was installed on the tow bar of the car. The two additional PN-PEMS (prototype NPET from Horiba (Kyoto, Japan) and Nanomet 3 from Testo (Lenzkirch, Germany)) were installed in the cabin of the vehicle. More details about the PN-PEMS can be found elsewhere [31], and their results will not be presented here. At some laboratories, one of the two PN-PEMS was not installed because it was not functioning, and at some other laboratories, a second person was inside the car, in addition to the driver. The additional weight associated with the instrumentation and one driver was typically around 125 kg, 24% of the maximum payload, but it varied between 20% and 40%, well below the 90% of the maximum payload, which is the maximum applicable payload limit defined by the RDE regulation.

The testing protocol included 3 days in the laboratory and 2 days on the road (with morning and afternoon tests). The laboratory tests were the applicable type approval cycle of the specific vehicle NEDC (new European driving cycle) and the current type approval cycle WLTC (worldwide harmonised light vehicles test cycle). The vehicles were soaked in closed garages with temperatures around 20 °C; thus, the influence of the external ambient temperature during cold start was small. The soak duration did not fully respect the Euro 6d and 6e RDE requirements (minimum 6 h), as tests were run in the morning and afternoon. The drivers were instructed to drive normally according to their laboratory procedures for RDE tests. They were allowed to turn on the heater or air-conditioning of the car. All laboratories used reference E5 fuel from the same batch with 5% ethanol, 31.7% aromatics, and 3 mg/kg sulphur content.

Before each trip, the analyzers were zeroed with nitrogen, and their maximum range was adjusted using span gases with 1% accuracy (2% for NO_2 in the first RDE package [20]). The span concentration range was different at each laboratory but fulfilled the requirement that the maximum concentration during a test should be lower than two times the span value, and all exceedances should be <1% of the total trip duration. At the end of the trip, the span ranges were controlled, and they were within 2%. The zero levels were also within 0.2% for CO_2, 10 ppm for NO_x, and 100 ppm for CO. Note that Euro 6d RDE specified a maximum drift of 5 ppm for NO_x and 75 ppm for CO. With Euro 6e, the maximum NO_x drift is 3 ppm. Each laboratory used its own personnel to operate the PEMS and drive the vehicle.

The data were analyzed in accordance with the rules of Regulation (EU) 2017/1151 [25] using EMROAD 6.04. A short description follows; the details can be found in the regulation. Instantaneous data were binned in urban (≤60 km/h), rural, or motorway (>90 km/h) parts, depending on the vehicle speed. The assessment was performed for the total trip and each sub-part. Initially, it was confirmed that the operation of PEMS was error-free, and the concentrations were within their calibrated range. The next step was the evaluation of the trip characteristics, such as urban, rural, motorway shares, altitude, temperature range, vehicle conditioning at cold start, cold start requirements, sub-part trip requirements (e.g., average speed, stop time), and cumulative altitude gain. No correction was needed and/or applied for extended ambient temperature or altitude conditions, as the conditions were within the moderate range. Then, the 95th cumulative percentile of speed × acceleration and the relative positive acceleration for each sub-part were calculated and compared with the respective limits. Finally, applying the moving average window, the CO_2 of each window was compared with the reference values from the type approval cycle. The calculation of the emissions (i.e., from ppm to mg/km) for the total trip and each sub-part was the next step. No drift correction was applied to the PEMS concentrations. The final emissions were not corrected with the PEMS margin (1 + 0.1 for NO_x given in Appendix 11 of Regulation (EU) 2023/443 for Euro 6e [24]). The analysis was performed without correcting for the RDE evaluation factor (as per Appendix 6 of Regulation (EU) 2017/1151 for Euro 6d [25] or Appendix 11 of Regulation (EU) 2023/443 for Euro 6e [24]). This factor is calculated as the ratio of the test (trip) CO_2 and the type approval cycle CO_2 and takes into account the severity of the trip. For ratios <1.3, no correction is applied, while for ratios >1.5, the inverse of the ratio is applied to the final emission result. For ratios in between, a linear function is used to calculate the final correction value. The effect of this correction will also be presented because it is included in the latest RDE regulation. For this correction, as the CO_2 value was not available at the certificate of conformity of the vehicle, we used the average cold start WLTC CO_2 value determined at the first laboratory.

Finally, the integrated results for the urban or the total trips were assessed following ISO 5725-2 [45] to determine the variance in the emissions following the same route (equations for within labs variance) and the variance in the emissions following different routes (equations for between labs variance) (see also [46] for simplified equations). The first is a weighted average of the laboratories' same route's "repeatability". The second is the weighted variability of the laboratories' averages. The analysis was carried out for each pollutant and CO_2. The analysis was also repeated, removing the first 300 s (cold start) in order to remove as much as possible the effect of the ambient conditions on the emissions associated with the cold start, such effect being substantial for gasoline vehicles [47]. Variance is a measure of variability, but in this text, we use the terms interchangeably. The final statistical analysis is not part of the regulation but is typical for the inter-laboratory correlation exercises.

3. Results

This section will present the three assessment steps: trip validity; emissions calculations; and statistical analysis. A total of 24 RDE road tests were performed at the premises of the seven participating laboratories, plus two more repetitions at the end of the campaign from the first laboratory. The trips were compliant with the first package RDE, and any deviations from the subsequent RDEs will be discussed.

3.1. Trip Characteristics

Table 2 gives the average ambient conditions during the various on-road trips. It should be remembered that the vehicle was soaked in temperature-controlled areas with an ambient temperature of around 20 °C. The ambient temperature during the RDE tests ranged between 3 °C and 25 °C (averages between 7 °C and 23 °C) with an overall average value of 14.2 °C. The ambient pressure of the trips ranged between 99 kPa and 103.9 kPa, with an overall average value of 102 kPa. The average relative humidity was around 60%. According to the regulation, all trips were carried out at "moderate" conditions.

Table 2. Average ambient conditions of the various trips.

Parameter	Units	#1a	#2	#3	#4	#5	#6	#7	#1b
Temperature	°C	23.1	17.3	11.6	15.5	16.9	8.3	13.9	7.0
Pressure	kPa	99.0	103.9	101.3	103.0	102.1	102.2	103.6	102.5
Relative humidity	-	61%	61%	57%	56%	60%	63%	59%	45%

Table 3 summarises the average trip characteristics and the respective limits set in the legislation. In general, the trips fulfilled the requirements with the exception of the cold start provisions. Most of the trips had an initial idling duration of >15 s and a cold start–stop time of >90 s, thus not fulfilling Euro 6d and Euro 6e RDE regulations. These requirements were not part of the draft requirements when the tests were conducted in 2015. They were added with the third part of the RDE legislation in 2017 with Regulation (EU) 2017/1154 [22], and, therefore, not fulfilling them does not explicitly violate the RDE requirements. In general, the average values were within 10% of each other. All laboratories followed the urban, rural, and motorway, in this order, except laboratory #7, which followed the urban, motorway, and then the rural part. It should be remembered that the order urban–rural–motorway became obligatory with Regulation (EU) 2016/427 [20], applicable from 2017.

Table 3. Average trip characteristics per laboratory. In *italics*, values that are outside of the Euro 6d RDE 4th package (Regulation (EU) 2018/1832) [23] specifications.

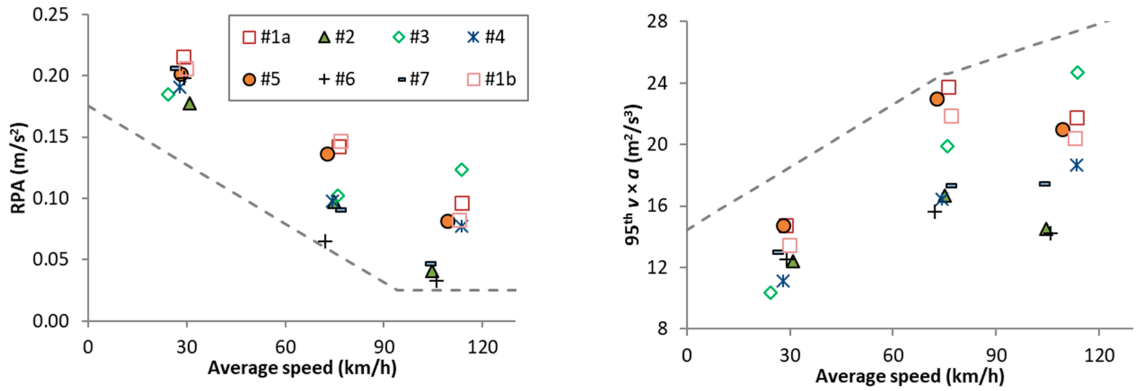
Parameter (RDE Thresholds)	Units	#1a	#2	#3	#4	#5	#6	#7	#1b
Number of valid trips	-	2	3	3	4	4	3	5	2
Total trip distance	km	78	74	82	88	82	97	83	79
Total trip duration (90–120)	min	92	*88*	109	105	107	113	107	93
Urban distance (>16)	km	29	27	30	31	34	33	29	31
Rural distance (>16)	km	25	24	27	30	27	29	26	23
Motorway distance (>16)	km	24	23	26	28	22	35	28	25
Urban distance share (29–44)	%	37	36	36	35	41	34	35	39
Rural distance share (23–43)	%	32	33	32	34	32	29	32	30
Motorway distance share (23–43)	%	31	31	31	31	27	36	34	31
Urban average speed (15–40) [1,2]	km/h	29	31	24	28	28	29	25	30
Rural average speed	km/h	76	75	76	74	73	72	75	77
Motorway average speed	km/h	114	105	114	114	109	106	103	113
Total trip average speed	km/h	51	52	46	50	46	52	47	51
Motorway speed >145 km/h (<3)	%	0	0	0	0	0	0	0	0
Motorway speed >100 km/h (≥5)	min	10	8	12	12	8	18	10	10
Urban stop time (6–30) [1,3]	%	24	16	23	21	17	17	27	20
Initial altitude	m	210	75	325	134	150	75	104	208
Altitude difference (≤100)	m	30	18	8	37	100	49	7	37
Total CPEG (<1200 m/100 km) [1]	m	615	452	872	262	413	338	801	645
Urban CPEG (<1200 m/100 km) [1]	m	628	455	944	246	410	447	840	767

Table 3. *Cont.*

Parameter (RDE Thresholds)	Units	#1a	#2	#3	#4	#5	#6	#7	#1b
Idling events >300 s [4]	Y/N	N	N	N	N	N	N	*Y*	N
Initial idling duration (≤15) [5]	s	*19*	8	*103*	*47*	*93*	*18*	*19*	11
Cold start average speed (15–40) [5]	km/h	*9*	15	18	24	*10*	18	16	22
Cold start max speed (<60) [5]	km/h	47	52	48	56	54	38	*74*	56
Cold start–stop time (≤90) [5]	s	*175*	74	*121*	69	*117*	38	*139*	47

[1] added to second package. This requirement has been softened in Regulation (EU) 2023/443 [24], and the test is invalid only if the final RDE emissions are above the limits; [2] it was 15–30 at first package; [3] it was >10; [4] at second package long idling was excluded from analysis. With third package, the trip is void. This requirement has been softened in Regulation (EU) 2023/443 [24], and the test is invalid only if the final RDE emissions are above the limits; [5] added with third package. CPEG = cumulative positive elevation gain.

The average trip dynamics are presented in Figure 1. The clouds of points at speeds 29, 72, and 106 km/h represent the urban, rural, and motorway parts, respectively. All trips respected the lower limits of relative positive acceleration (RPA) and the upper limits of the product of velocity and acceleration ($v \times a$), with some of the trips close to the limits, although they were introduced as requirements later [21].



(**a**) (**b**)

Figure 1. Average trip dynamics for the different laboratories: (**a**) relative positive acceleration (RPA); (**b**) 95th percentile of velocity per positive acceleration. Both in function of the average speed of urban, rural, and motorway parts. The dashed lines correspond to the RDE thresholds.

The average exhaust flow rate of the total trip was 35 kg/h, and for the urban part, it was 25 kg/h. The peaks at the various trips reached 160–210 kg/h, thus covering 64–84% of the flow meter range. Amendment of the RDE regulation in Regulation (EU) 2018/1832 [23] recommends having the maximum expected flow rate during the test covering at least 75% of the EFM full range.

3.2. On-Road Emission Results

Real-time examples of emissions of the specific vehicle can be found in Figure A1 in Appendix A. In general, the pollutant concentrations were high at the cold start and at the motorway part.

Table 4 summarises the maximum concentrations and the 90th percentile of the analyzers' signals that were measured during the campaign. The span gas concentrations that were used for the calibration of the analyzers were in accordance with the regulation. They covered at least 90% of the concentration values obtained from 99% of the measurement of the valid parts of the emissions test. The RDE concentrations were not more than double the span gas ranges. What is impressive is that while the peaks of CO exceeded 12,400 ppm, the majority of the concentrations during the trips were <255 ppm. To a smaller degree, this happened also to NO. These results show the wide range that the analyzers must cover and the importance of accurate linearization, even at low concentrations. It also indicates that any drift might have an impact on the final result [32].

Table 4. Maximum and 90th percentile of the analyzers' RDE (wet) concentration signals and span gas ranges. Range gives the maximum measured concentrations at all laboratories.

Parameter	PN × 10^6 (#/cm^3)	CO_2 (%)	CO (ppm)	NO (ppm)	NO_2 (ppm)
Maximum	3.3–17	13.7–14.1	12,400–26,600	830–2300	5–50
A 90th percentile	1.2–3.1	13.4–13.7	75–255	38–170	0–17
Span gas range	-	14.8–18.0	7600–16,000	870–1940	210–510

Figure 2 presents the average results of the trips for each laboratory for CO_2, NO_x, and PN for the urban part (left panels) or the total trip (right panels), including the cold start. The tests of the first laboratory at the start and end of the inter-comparison exercise were quite close to each other. The PN and NO_x were around 15% lower at the end of the testing, and CO_2 was 9% higher. The CO (not shown) was around 30% higher. However, the tests in the second period were carried out at 7 °C, while in the first period, at 23 °C of the ambient temperature, which can explain such differences.

Even though it is not meaningful to perform a statistical analysis with only two repetitions, the differences between the urban part and the total trip were not statistically significant, except for NO_x for the total trip. Nevertheless, based on the laboratory means, there was no obvious drift for the combination vehicle and instrumentation.

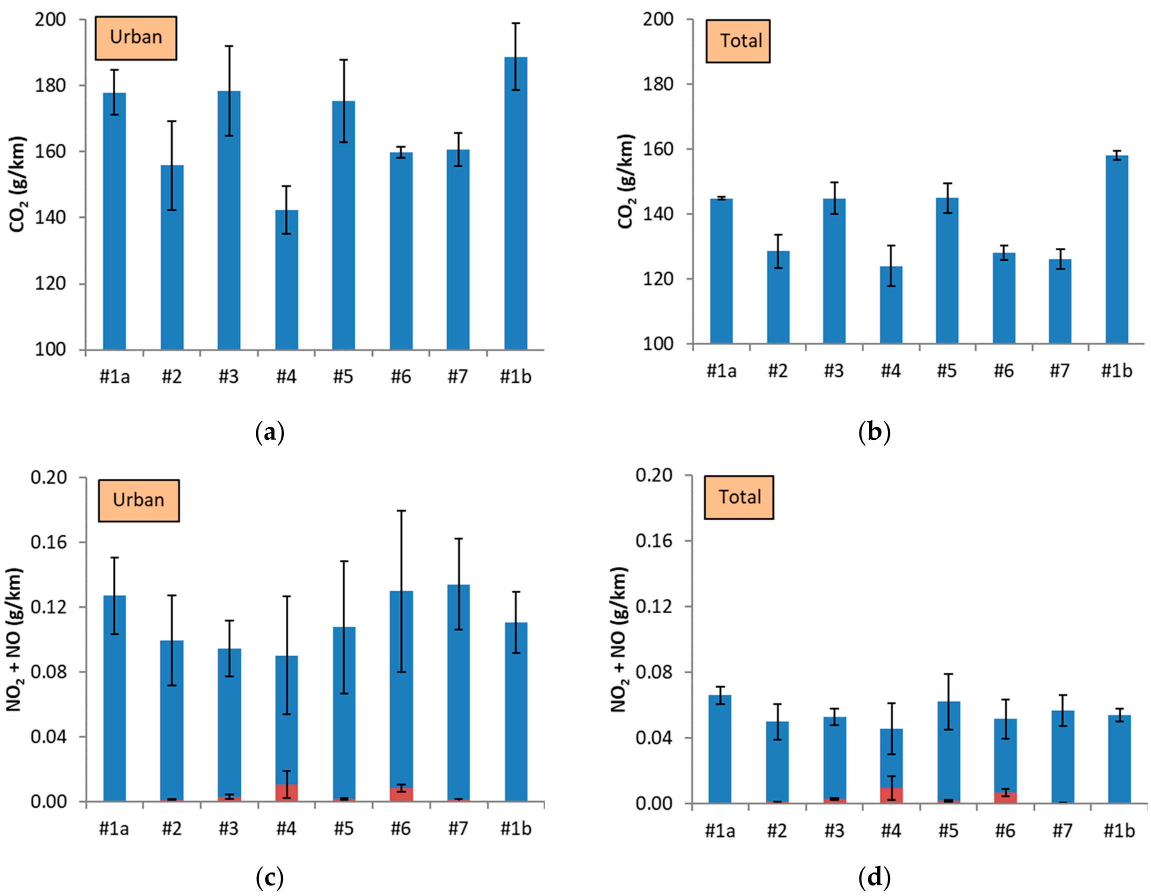
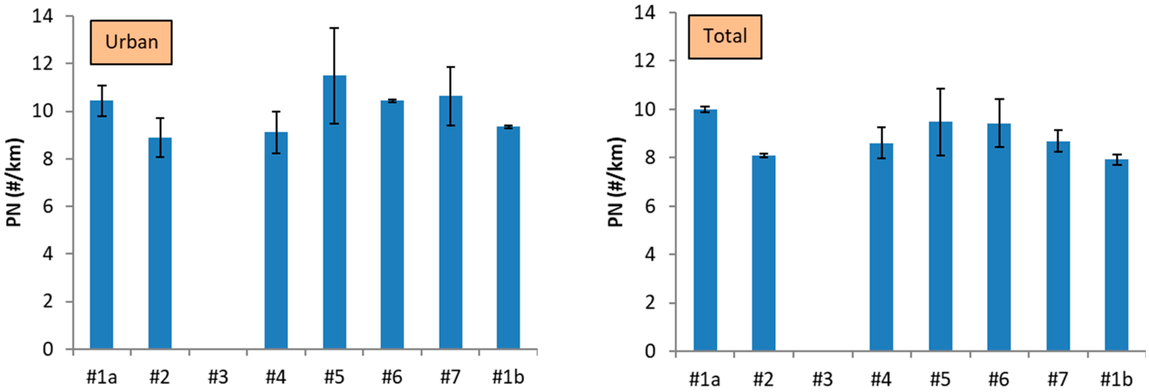


Figure 2. *Cont.*



(**e**) (**f**)

Figure 2. Average trip results for each laboratory for urban parts (left panels) and total trips (right panels): (**a**) CO_2 urban; (**b**) CO_2 total; (**c**) NO_x (NO_2 red, NO blue bars) urban; (**d**) NO_x (NO_2 red, NO blue bars) total; (**e**) PN urban $\times 10^{11}$ #/km; (**f**) PN total $\times 10^{11}$ #/km. Cold start is included in urban part. Error bars show one standard deviation of two to five repetitions. No PN measurements available for laboratory #3.

Regarding the tests at all laboratories for CO_2, two distinct levels could be seen for the total trip: around 145 g/km (Labs #1, #3, and #5); and around 125 g/km (Labs #2, #4, #6, and #7). The high CO_2 group had an additional passenger (Lab #1), lower ambient temperature, use of a heater or air conditioning and/or higher $v \times a$. The variability (i.e., error bars) of the total trip was almost half (1–6 g/km) of the urban part variability (2–13 g/km).

NO_x ranged between 45 and 65 mg/km for the total trip without any particular trend. NO_x was ~100 mg/km in the urban part and had a rather high scatter. NO_2 was negligible, with values from 0 up to 9 mg/km. The trips with higher NO_2 emissions were those that had an increasing trend of NO_2 over time, which was due to the drift of the analyzer (see example Figure A1 in Appendix A). The NO_x variability (error bars) was around 5–16 mg/km for the total trip and 23–48 mg/km for the urban part.

PN varied in a narrow range of around 9×10^{11} #/km without any particular trend. The variability (error bars) was 0.1–1 $\times 10^{11}$ #/km for the total trip and 0.1–2 $\times 10^{11}$ #/km for the urban part.

3.3. Statistical Analysis

The results of the statistical analysis according to ISO 5725-2 for the variance in the emissions following the same or different routes are given in Table 5. Only the first tests of Lab #1 were considered in the analysis in order to avoid having two data sets from the same laboratory and bias the results. No laboratory was removed from the analysis based on the Grubbs and Cochran tests. The variance in the same route (within routes variability) for the total trips was 2.9% for CO_2, around 24% for CO and NO_x, and 6% for PN. The variance in different routes (between routes variability) was 7% for CO_2, 9% for CO, negligible for NO_x, and 9% for PN. The very low value for NO_x has to do with the high scatter of the repeats at the laboratories, making the contribution of the variability of the means at all laboratories negligible. While the means at each laboratory were within 20% of the mean value, the variability at the labs was 18–41%. One interesting finding is that the variance in the emissions following the same route was higher than following different routes for CO and NO_x, while the opposite applied to CO_2. This will be discussed in the Discussion section, but it indicates that CO_2 is sensitive to conditions such as weight and driving dynamics, while CO and NO_x depend more on the cold start part of a trip. The last column, "Combined", combines within and between variances and practically gives the expected variance in the vehicle as measured at different locations. It is calculated as the square root of the sum of the squares of the two values. It is the equivalent of "reproducibility" of laboratory tests, although this term cannot be used for on-road tests (see Section 1).

Table 5. Statistical analysis of the results. "CO_2 corr." refers to correction of Appendix 6 of Regulation (EU) 2017/1151 [25] or Appendix 11 of Regulation (EU) 2023/443 [24]. "Hot" refers to test removing the initial 300 s.

Pollutant	Trip Part	Mean	Same Route	Different Routes	Combined
CO_2	Urban (cold)	164.7 g/km	4.9%	7.4%	8.8%
	Urban (hot)	160.0 g/km	7.1%	12.0%	13.9%
	Total (cold)	134.6 g/km	2.9%	6.9%	7.5%
	Total (hot)	131.9 g/km	3.3%	7.4%	8.1%
CO	Urban (cold) CO_2 corr.	81 mg/km	34.1%	0.0%	34.1%
	Urban (cold)	113 mg/km	29.0%	4.9%	29.4%
	Urban (hot)	18 mg/km	32.4%	18.4%	37.2%
	Total (cold) CO_2 corr.	70 mg/km	22.6%	0.0%	22.6%
	Total (cold)	77 mg/km	23.8%	9.1%	25.5%
	Total (hot)	43 mg/km	26.5%	4.3%	26.9%
NO_x	Urban (cold) CO_2 corr.	80 mg/km	29.4%	1.0%	29.4%
	Urban (cold)	113 mg/km	30.6%	0.0%	30.6%
	Urban (hot)	104 mg/km	26.6%	3.0%	26.8%
	Total (cold) CO_2 corr.	50 mg/km	22.9%	0.0%	22.9%
	Total (cold)	55 mg/km	23.0%	0.0%	23.0%
	Total (hot)	51 mg/km	20.0%	9.8%	22.3%
PN $\times 10^{11}$	Urban (cold) CO_2 corr.	7.3 #/km	14.2%	1.7%	14.3%
	Urban (cold)	10.2 #/km	11.6%	7.2%	13.7%
	Urban (hot)	9.3 #/km	11.2%	6.2%	12.8%
	Total (cold) CO_2 corr.	8.5 #/km	6.0%	4.7%	7.6%
	Total (cold)	9.2 #/km	5.8%	9.1%	10.8%
	Total (hot)	8.9 #/km	6.0%	9.2%	10.9%

The results did not change significantly, correcting with the CO_2 a ratio of a trip to laboratory certification cycle. Excluding the first 300 s of the trips and repeating the analysis (i.e., trips with hot start) did not improve the coefficient of variances. However, the absolute emissions were lower, especially for CO, which is usually mostly associated with the cold start emission, and thus, the absolute variances were lower (but not the relative variance).

4. Discussion

This is the first study to compare RDE-compliant routes at different locations in Europe using the same car and PEMS. Even though the original objective was to assess the measurement uncertainty of PN-PEMS (see [44]), the data were proven to be useful for the assessment of the trip variance following the RDE procedure, the variance following the same route and the variance following different routes at different locations. In general, the results of an RDE test depend on the vehicle and its stability, the influence of the operating conditions on the vehicle emissions, and the measurement accuracy of the measurement equipment. In this inter-laboratory exercise, the circulation of a "Golden" (reference) PEMS made it possible to exclude (or minimize) the uncertainty related to the use of different equipment. This does not mean that the results were necessarily the "true" emissions, but any bias of the instrument should be similar at all locations. Testing at the chassis dynamometers of the laboratories with two cold start NEDCs (new European driving cycle) and five hot start WLTCs (worldwide harmonised light vehicle test cycle) showed that the average deviations of PEMS to laboratory (bag) results were +9.4% (with one standard deviation ±2.9%) and +7.5% (±3.6%) for CO_2 for the NEDCs and WLTCs, respectively, and +17.3% (±25.0%) and +2.0% (±17.5%) for NO_x. Nevertheless, the differences were in most cases within the permissible tolerances prescribed in the RDE regulation for the CO_2 (maximum difference between PEMS and laboratory 10 g/km or 10%, which was reduced to 7.5% with Regulation (EU) 2023/443 [24]) and NO_x (15 mg/km or 15%, which was reduced to 10 mg/km or 12.5% with Regulation (EU) 2023/443). Similar differences for the same PEMS model were found by others [48]. While the PEMS vs. laboratory differences for NO_x were not statistically significant, for CO_2, they were. Typically, CO_2 analyzers are accurate within 2%; thus, the difference indicates that the specific flow meter was overestimating the flow. Indeed, the CO_2 deviation was similar to the difference in the PEMS flow to the exhaust flow calculated by the laboratory (total dilution tunnel flow minus dilution air) [44]. Although the CO_2 is not included in the RDE pass/fail criteria, it can invalidate a test based on the overall trip dynamics requirement with the moving average window (MAW) (as defined in Appendix 5 of RDE regulation Annex IIIA [25]), and it can indirectly affect the results by the correction with the CO_2 ratio of RDE to laboratory WLTC (Appendix 6 of the same RDE regulation). Other studies showed that the PEMS uncertainty can be as high as 43% for NO_x and 50% for PN, but in most cases, it should be less [31,32]. Inter-laboratory PEMS exercises gave differences of <4% for CO_2, 10–20% for NO_x, and 35–40% for PN (the assessment was performed in the laboratory) [46,49].

The emissions of the "Golden" circulating vehicle with a gasoline direct injection engine and a three-way catalyst remained relatively stable over the exercise. The tests of the first laboratory at the start and end of the exercise had some differences (PN and NO_x were 15% lower, CO 30% higher, and CO_2 was 9% higher at the end of the testing). The lower ambient temperature, the use of the heater or air-conditioning, and the slightly higher $v \times a$ of the trips at the end of testing can partly explain this trend for CO_2 [50].

With the exception of the cold start, three-way catalysts work efficiently, and emissions of CO, HCs (that were not measured in this study), and NO_x are generally low. Higher emissions can be seen at deviations of stoichiometric mixture [51,52], e.g., dynamic driving with hard accelerations [53] or high engine loads, which was not the case of the conducted trips. The direct injection engine was proven to be a stable and substantial source of particles as well [54]. The urban and total trip emission levels of NO_x (113 mg/km and 55 mg/km) and PN (10.2×10^{11} and 9.2×10^{11} #/km) were close to the limit or slightly higher than the limits for Euro 6d gasoline vehicles ($60 \times 1.43 = 86$ mg/km for NO_x and $1.5 \times 6 \times 10^{11} = 9 \times 10^{11}$ #/km for PN), although not applicable to this car (type approved as Euro 5). RDE studies with Euro 5 and Euro 6b/c GDI vehicles without gasoline particulate filter (GPF) found emission levels between 20 and 83 mg/km for NO_x and 0.6 and 1.7×10^{12} #/km for PN [55,56].

The environmental and driving conditions (Table 2), in general, varied in a narrow range, well below the temperature boundaries of the extended conditions (0 °C and 30 °C). Regulation (EU) 2023/443 increased the maximum extended ambient temperature from 35 °C to 38 °C, starting with Euro 6ebis (in force 01/01/2025). It also softened this requirement by invalidating a test only in case the emissions were above the limits. Even though the ambient temperature varied in the range of 3 °C to 25 °C (mean temperatures between 7 °C and 23 °C), all laboratories soaked the vehicles in a temperature-controlled area with ambient temperature around 20 °C, minimizing the effect of external temperature on the cold start emissions and the impact of using auxiliaries (e.g., air conditioning). It is highly likely that the scatter would be higher if the vehicle was soaked outside. Since the third package (2017/1154) [22], if the vehicle is conditioned for the last three hours prior to the test at an average temperature that falls within the extended range, then the 1.6 extended factor applies to the cold start period, even if the running conditions are not within the extended temperature range. The rest of the trip characteristics, such as distances, shares, etc., also varied in a relatively narrow range (typically within ±10%). Bigger variability of the trip characteristics was noticed at the cold start part. The reason was that the testing was conducted before the introduction of RDE in the regulation, and in particular, the third package that introduced the new provisions regarding idling duration and cold start average speed; so, in some cases, the results were not compliant to the Euro 6d or later RDE requirements. Note that with Regulation EU 2023/443 [24], the test is invalid only if the final emissions exceed the limit. Nevertheless, repeating the statistical analysis excluding the first 300 s (cold start), no improvement in the (relative) variance values was noted (partly explained by the lower absolute emission factors). The removal of cold start reduced the absolute emissions by 3% for CO_2, 84% for CO, 7% for NO_x, and 8% for PN for the urban part. The contribution of cold start was higher [56] or similar [4,57] to what has been reported by others for RDE trips. The relative contribution depends on the absolute emissions during the cold start period but also on the absolute emissions at the rest of the test and the trip duration. For pollutants such as CO, where the majority of the emissions occur at the cold start, the inclusion or not plays an important role.

Repeating the analysis using the pollutant emissions corrected with the RDE evaluation factor (see Section 2: CO_2 ratio of the trip to the certification cycle; practically normalizing the emissions to the same CO_2 emissions), did not change the variances. This implies that the dependence of CO, NO_x, and PN on the CO_2 or power of the vehicle is small for properly operating after-treatment devices and the small range of CO_2 of this study.

In one laboratory, the order of testing was not urban, rural, and motorway, but urban, motorway, and rural (Lab #7). No differences were seen compared to the rest of the laboratory trips for the rural and motorway parts. Later amendment with Regulation (EU) 2018/1832 [23] defined that the order has to be urban, rural, motorway.

A few labs (#1, #5) had higher driving dynamics than some others (#6, #2, #7), but still well within the RDE boundaries (see Figure 1). This was also evident at the CO_2 values (Figure 2a,b) but not at the other pollutants (Figure 2c–f). This indicates that the vehicle could control the emissions within the boundaries of the regulation well.

The lack of NO_2 zero checks and/or the 10 ppm permitted drift at that time (5 ppm for NO and 5 ppm for NO_2) resulted in high NO_2 measurements scatter (0–9 mg/km). This drift, however, did not impact the NO_x variance as NO_2 was <15% of NO_x. Euro 6e RDE regulation [24] allows for a maximum (total) NO_x drift of 3 ppm and drift correction on the instantaneous values.

In addition to the differences in routes, the different driving dynamics, the lack of weight control, and air conditioning use influenced the CO_2 variance [50,58]. The big variability of CO_2 under real conditions is well known. A study that monitored the fuel consumption (almost proportional to CO_2 emissions) of a single vehicle throughout one year with twenty different persons using and driving the vehicle found deviations of ±14% (one standard deviation) [59]. Our results also showed a scatter of 8-14% for urban or total trips with cold or hot engine start, highlighting the difficulties in assessing CO_2 (and fuel consumption) with on-road trips. Nevertheless, the results give an indication of the variance in the same or different routes under normal RDE conditions; thus, they could be useful for researchers who declare or interpret RDE results with gasoline-fueled vehicles. It should be emphasized that the results include the variability of the vehicle. In our case, it was proven to be relatively constant after >4000 km of driving; thus, they give a good indication of the RDE testing procedure. However, for other vehicles and different environmental or trip conditions, the variability of the vehicle emissions could be much higher. This depends on the calibration and strategy of the engine and/or aftertreatment devices. For example, NO_x emissions of diesel vehicles are more difficult to control and could depend on the ambient temperature [38,39,48,60], the exhaust gas temperature [61,62], the use of the exhaust gas recirculation (EGR) [63], or regeneration events [64]. It is also well known that more dynamic driving (with harder accelerations) (or expressed as higher $v \times a$ or RPA) will increase the emissions and, consequently, the variance in the results [12,61,65–69]. The traffic, the road grade, the altitude, and the wind also have an effect on CO_2 and pollutants [60,70–74]. In general, vehicle-specific power (VSP) is correlated with emissions [75], and the use of auxiliaries, e.g., air conditioning, can also influence the results [38,39,50]. For PN, the existence of a particulate filter and vehicle hybridization can also increase the variability [76]. Thus, more complex aftertreatment devices (such as those installed in Euro 6d vehicles and later), wider ambient temperatures, more dynamic driving and wider changes in altitude will increase the scatter (and variance) due to their greater influence on the vehicle emissions.

Due to the wide range of environmental and trip conditions, RDE regulation was designed as a pass–fail test and not for comparisons of vehicles. Here, we gave the variability ranges of the same or different routes under moderate RDE conditions, including cold start. If, however, the objective is the comparability of vehicle emissions, then the guidelines of the European Committee for Standardization (CEN) Workshop Agreement (CWA) 17379:2019 should be followed [77]. The standard was built upon the RDE methods and defined a process to test the emissions during urban driving, with the aim of comparing the on-road emissions performance of different vehicles. Among others, some requirements include trips of at least 10 km long, with a hot engine, at ambient temperatures between 10 °C and 20 °C, and average speed between 20 km/h and 40 km/h. According to this CEN, to compare emissions between vehicle models, it is necessary to collect at least five valid trips from at least two different vehicles of the specific model, fulfilling the above-mentioned requirements.

One final note is that the PEMS measurement uncertainty is different from the "route" variability values that were discussed here. Two trips at two locations with two different PEMS could have differences that combine the two factors (trip influence and PEMS influence).

In closing, it should be emphasized that the variance following the same route is at acceptable levels, comparable to chassis dynamometer laboratory repeatability for the gaseous pollutants (but not for CO_2). For example, reported repeatability for the NEDC cycle can be <0.5% for CO_2 (at 200 g/km), but for NO_x (at 20 mg/km), it can be 15% or higher, especially for PN [78–80].

Similarly, the laboratory reproducibility based on inter-laboratory correlation exercises compared to RDE is lower for CO_2 (2%) and lower-to-similar for the rest of the pollutants (10–30%) [46,81]. The variance in the CO_2, NO_x, and PN for the cold start NEDC and hot WLTC of the laboratories that participated in our study was 2.1–2.3%, 20–37%, and 20–22%, respectively [44].

5. Conclusions

A Euro 5b gasoline direct injection vehicle with a portable emissions measurement system (PEMS) was circulated at seven European laboratories. Trips compliant with the European Union's (EU) real-driving emissions (RDE) regulation were conducted at the premises of the laboratories. The variance in different routes around Europe was 7% for CO_2, negligible for NO_x and 9% for PN and CO. The variance following the same route was 3% for CO_2, around 24% for CO and NO_x, and 6% for PN. The data showed that the variance in CO and NO_x repeating the same route (24%) could be higher than following different routes (<9%). The opposite was noticed for CO_2 (7% vs. 3%). For PN, both the same and different route variances contributed to the final result. The results of this study indicate that the NO_x and CO emissions at different locations could be comparable under similar environmental (temperature, altitude) conditions and trip characteristics (dynamics, shares of urban/motorway parts). For CO_2, though, stricter protocols and control of conditions are necessary if results need to be compared. When trip emissions are compared, though, in addition to the trip influence that was discussed in this study, the PEMS uncertainty should be taken into account. Finally, the variance values derived from the Euro 5b gasoline direct injection vehicle with the three-way catalyst of this study do not necessarily apply to more advanced or different combustion and aftertreatment technologies (e.g., hybrids or diesel with selective catalytic reduction for NO_x).

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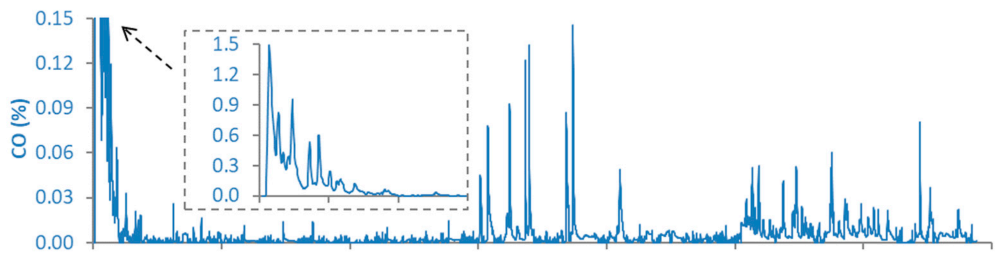
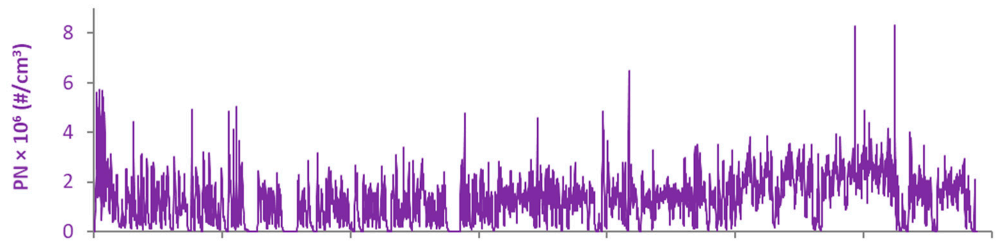
Appendix A

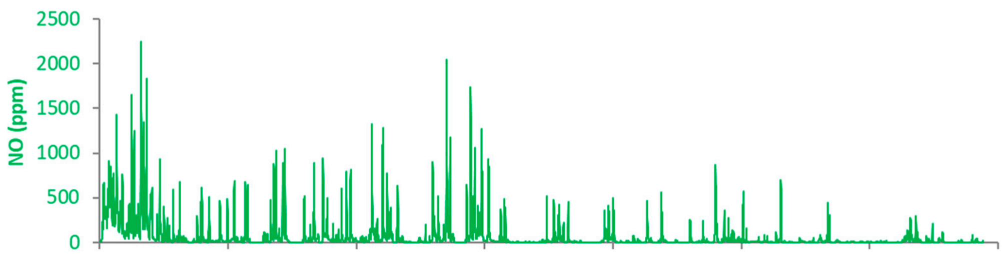
Figure A1 gives an example of real-time signals of the wet concentration of CO, PN, NO, NO_2, and CO_2. As the speed profile reveals (bottom of the figure), the first 3100 s are the urban part; then the rural part continues until 5000 s and then the motorway part. Gasoline engines work stoichiometrically, so the CO_2 is relatively constant, around 13.8%, with lower values at fuel cut-offs. The NO_2 is very low, while NO is emitted during a cold start (when the catalyst temperature is low) and decelerations (lean conditions and lack of oxygen reduce the conversion efficiency). The gradual increase in NO_2 up to 5 ppm for this particular example is an indication of the analyzer's drift. PN is high during the whole cycle, particularly at cold start and accelerations (note that this vehicle is not equipped with a particle filter). CO is very high during the cold start but is practically at zero when the catalyst reaches its light-off temperature; then, there are a few spikes during accelerations and some emissions at high speeds, probably because the exhaust flow is higher than the oxidation capacity of the catalyst and/or poor lambda management.



(**a**)

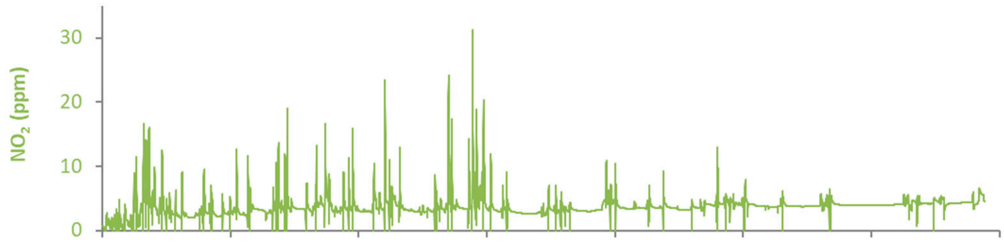


(**b**)

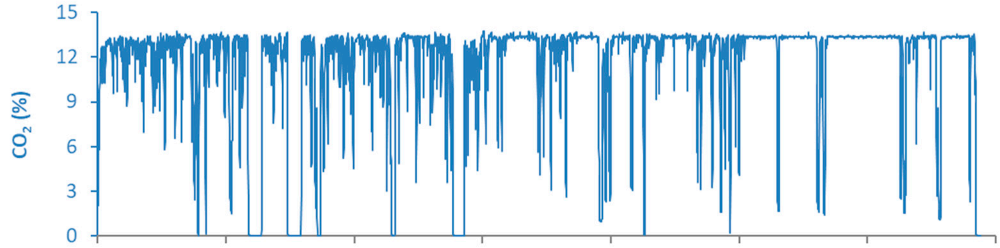


(**c**)

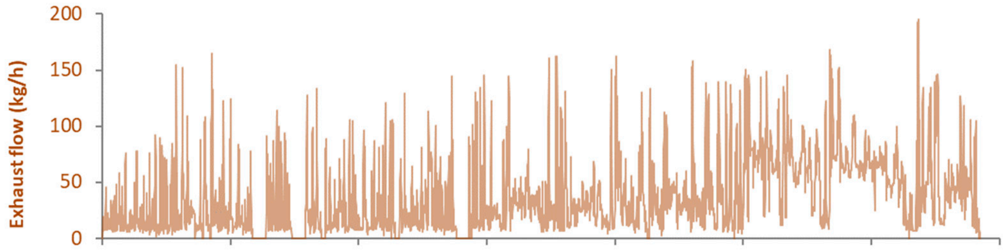
Figure A1. *Cont.*



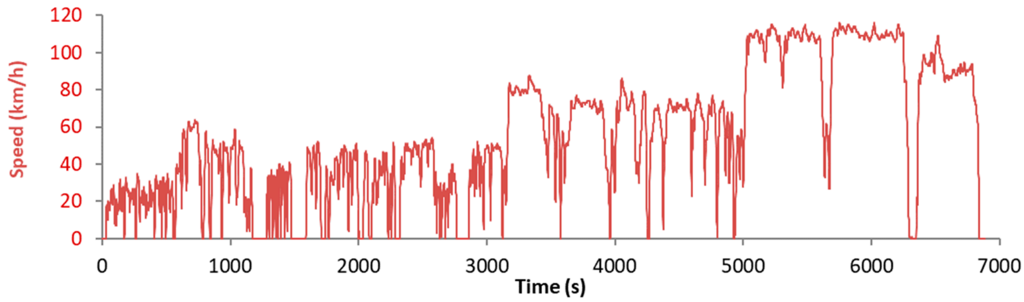
(**d**)



(**e**)



(**f**)



(**g**)

Figure A1. Real-time example of emission profiles during an RDE trip of laboratory #5: (**a**) CO; (**b**) PN; (**c**) NO; (**d**) NO_2; (**e**) CO_2; (**f**) exhaust flow rate; (**g**) speed.

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