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Date

August 28, 2017

Client

International Council on Clean Transportation (ICCT)
Neue Promenade 6
10178 Berlin
Germany

Final report

EMISIA SA Report

No: 17.RE.004.V1

Real-world emissions testing on four vehicles

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Project title	Call for Tender No:
Real-world emissions testing on four vehicles	By invitation
Document Title	Contract No:
Draft final report	No contract
Project Manager	Contractor:
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Summary

This report summarizes the work conducted by EMISIA SA and LAT in the context of a testing campaign and experimental study funded by the International Council on Clean Transportation (ICCT). The work is related to the emissions testing on four vehicles of different technology, all of which Euro 6 compliant, and under various driving conditions, both in laboratory and on-road. To this aim, a Portable Emissions Measurement System (PEMS) was employed for RDE measurements, while a number of driving cycles (NEDC, WLTC, Artemis) were tested on the chassis dyno of LAT. On-road testing included two different routes, a conventional one being compliant with RDE regulation, and a dynamic one characterized by abrupt driving and high altitude. The lab testing included also measurements at low ambient temperature, below the lower limit foreseen by the relevant regulations. All lab testing was conducted using real-world road load, determined by a coast-down test, while a NEDC test with official road load was also run.

Keywords
RDE, PEMS, Emissions measurement, NEDC, WLTC, real-world driving

Internet reference			
No internet reference			
Version / Date		Classification statement	
Revised Version / August 28, 2017		Confidential	
No of Pages	No of Figures	No of Tables	No of References
37	39	45	–

Approved by:

Giorgos Mellios

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Contents

1 Introduction

This report summarizes the work conducted by EMISIA SA and LAT in the context of a testing campaign and experimental study funded by the International Council on Clean Transportation (ICCT). The work is related to the emissions testing on four vehicles of different technology, all of which Euro 6 compliant, and under various driving conditions, both in laboratory and on-road using a Portable Emissions Measurement System (PEMS). Emisia is an official spin-off company of the Aristotle University of Thessaloniki/Laboratory of Applied Thermodynamics (LAT/AUTh) and has taken over the area of road transport emission inventories and projections, through a special contract with the Aristotle University of Thessaloniki.

In the following sections of this report, the methodology is described together with its implementation in the testing campaign, followed by the presentation of the results, separately for each vehicle and for all the testing conditions and measurements conducted.

1.1 Background

The ICCT commissioned laboratory and real-world PEMS emission measurements to monitor the emissions of modern passenger cars, in order to better understand the underlying reasons for the in-use discrepancies, both for CO_2 and exhaust emissions and to develop solutions for more realistic vehicle testing in the future. In this context, ICCT was particularly interested in better understanding the role of test cycle determination and adapted engine strategies for type-approval testing.

The objective of the study was to collect instantaneous emissions data, including CO_2, from a number of Euro 6 diesel and gasoline passenger cars over a number of representative test routes. The RDE-compliant measurements were conducted in accordance to the provisions of the relevant procedure. The main activity of the work covered the measurements, while some data processing analysis was also included.

1.2 Objectives of the work

The principal objectives of this contract were:

- To assess vehicle behavior and emissions during real-world driving with on-road testing.
- To evaluate the emissions performance of four modern vehicles with different engine and aftertreatment technologies in chassis dyno testing.
- To properly present the above in a final report.

2 Methodology & Implementation

2.1 Vehicle sample

The four vehicles tested in this study were the following:

- Vehicle 1 (LNT): BMW 520d 2.0
- Vehicle 2 (LNT): Nissan Pulsar 1.5dCi
- Vehicle 3 (SCR): Opel Insignia 2.0 CDTI
- Vehicle 4 (GDI): VW Polo 1.2TSI

All four vehicles were procured from rental companies, either local ones or from abroad. An overview of the technical specifications of the tested vehicles is provided in Table 1.

Table 1: Overview of tested vehicles technical specifications

Parameter	BMW 520d	Nissan Pulsar	Opel Insignia	VW Polo
MY & Chassis type	2015, Sedan	2016, Hatchback	2016, Station wagon	2015, Hatchback
Engine	Diesel, 4-cyl	Diesel, 4-cyl	Diesel, 4-cyl	Gasoline, 4-cyl
Drive & Transmission	RWD, Automatic	FWD, Manual	FWD, Manual	FWD, Automatic
Number of gears	8	6	6	7
Max power [kW]	140	81	125	66
Engine capacity [cm^3]	1995	1461	1956	1197
Start-stop	Yes	Yes	Yes	Yes
Euro class	6	6	6	6
Aftertreatment system	DOC, DPF, LNT	DOC, DPF, LNT	DOC, DPF, SCR	TWC
Type approval CO_2 [g/km]	109	94	124	109
Mileage (start of testing) [km]	16,630	27,540	20,560	5,930

2.2 Description of the experimental campaign

The present experimental campaign concerned the evaluation of emissions performance of the four vehicles mentioned above. Each vehicle underwent, in order, the following tests (before each test fault memory was read and reset, if necessary):

- On-road testing over different routes covering both the requirements of Real Driving Emissions (RDE) regulation and the conditions of more dynamic driving.
- Coast-down testing in a suitable track, in order to derive the realistic Road Load (RL) of each vehicle.
- Laboratory testing under certification and real-world driving cycles, applying realistic RL. In addition, one NEDC test was conducted with the official RL.

2.2.1 On-road testing

The first part of this experimental campaign was the on-road testing of the vehicles. The measurements were conducted with a Portable Emissions Measurement System (PEMS) that is available at LAT (Figure 1). This is the "AVL GAS PEMS iS" with its system control unit "MOVE" (IndiCom Version: 2.6). The main technical features of the PEMS equipment are given in Table 2. By the time of running these tests, the exhaust flow meter was not available, therefore the exhaust gas flow was calculated using the inlet air flow recording from the OBD.

Figure 1: PEMS installed on the VW Polo (left) **–** PEMS and control module (right)

Table 2: Technical characteristic of AVL GAS PEMS iS

Gas	**Range**	**Accuracy**
CO	Linearized range: 0 – 49999 ppm Display range: 0 – 15% vol	0-1499 ppm: ±30 ppm abs 1500-49999 ppm: ±2% rel.
CO_2	0 – 20% vol	0-9.99% vol: ±0.1% vol abs 10-20% vol: ±2% rel.
NO	0 – 5000 ppm	±0.2% FS or ±2% rel.
NO_2	0 – 2500 ppm	±0.2% FS or ±2% rel.
O_2	0 – 25% vol	±1% FS

On-road testing was conducted in the city of Thessaloniki (Greece) and its suburbs and included two different routes, as follows:

- One route complying with the RDE regulation, called "ThessTrip".
- One route representing the conditions of more dynamic (DYN) driving, called "ThessTrip Mountain".

➢ **RDE compliant route: ThessTrip**

This route has been designed according to the regulation for RDE testing of light passenger and commercial vehicles. It consists of three separate parts, namely Urban, Rural and Motorway, driven in this order. Figure 2 illustrates this route and Table 3 gives its characteristics. As shown below, the chosen trip meets all the requirements of the regulation. In addition, it has been tested on normal working days and all the characteristics were within the specified limits.

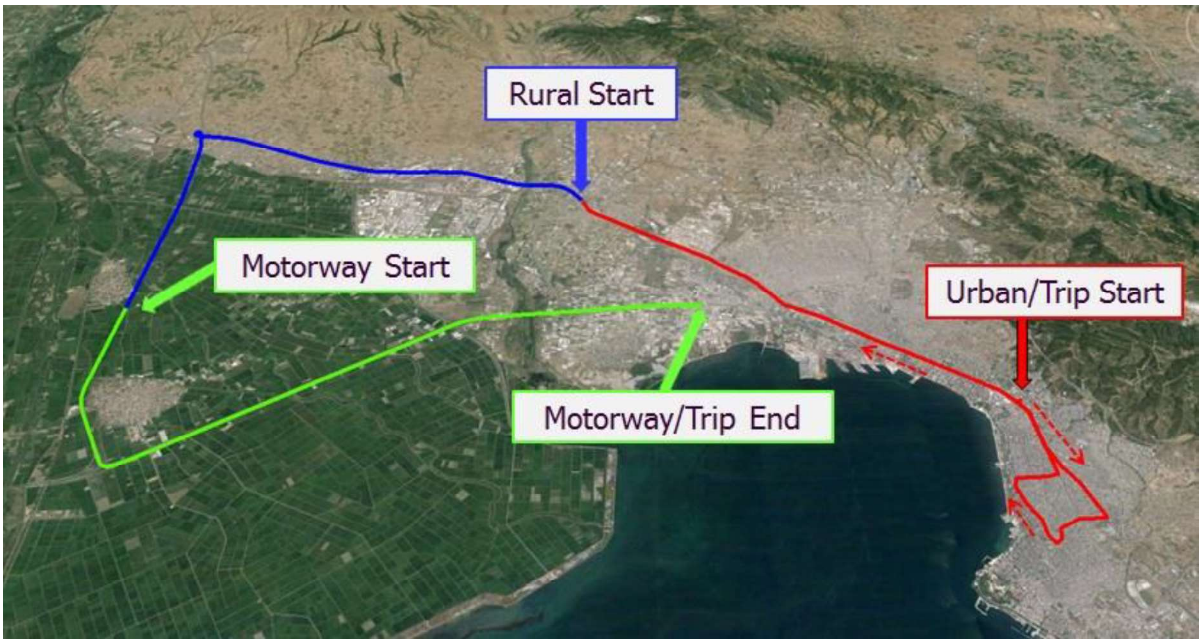


Figure 2: The route for measuring RDE emissions, complying with the regulation

➢ **Dynamic driving trip: ThessTrip Mountain**

This trip has been designed in order to represent a route with more dynamic characteristics than the previous one. It also consists of Urban, Rural and Motorway parts, but these are not necessarily driven in a specified sequence. It includes uphill/mountain driving with the maximum altitude difference between the highest and the lowest point in the order of 500m. Figure 3 illustrates this route and Table 3 summarizes its characteristics.

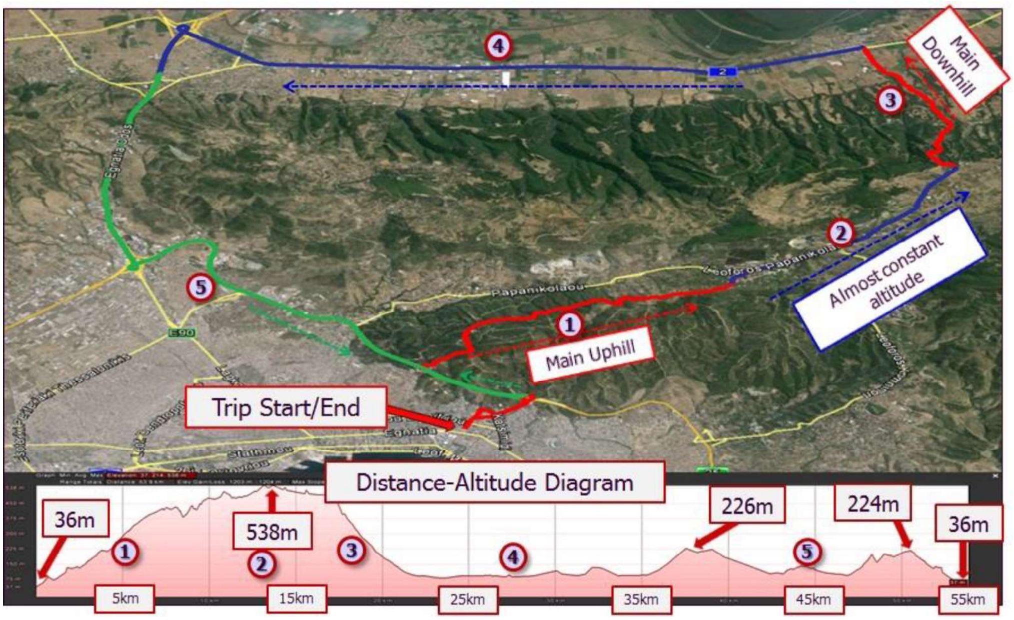


Figure 3: The route for measuring RDE emissions during dynamic driving

Table 3: Characteristics of the two routes considered in the study

Parameter	ThessTrip	ThessTrip Mountain	Regulation limits
Trip distance [km]	77	54	>48
Trip duration [min]	100-110	65	90-120
Maximum speed [km/h]	130	140	<145
Altitude difference end-start [m]	-10	0	<±100
Max Slope (Uphill/Downhill) [%]	4.2/-6.5	11.7/-17.6	-
Cumulative positive elevation gain [m/100km]	500	1700	<1200
Road type sequence	Urban-Rural-Motorway	mixed	-
Road type distance share (Urban(U)-Rural(R)-Motorway(M)) [%]	36.1-32.5-31.4	-	Approximately 34-33-33 (U:29%-44% R:23%-43% M:23%-43%)

2.2.2 Coast-down testing

After completing the on-road testing and before bringing the vehicle in the laboratory, the coast-down test was conducted. This test consists of free deceleration (gearbox in neutral, for both manual and automatic transmissions) of the vehicle after having accelerated up to a speed of 130 km/h and it is intended to provide the actual resistance applied on the vehicle during road driving. This resistance is the so-called "realistic RL" and it may differ from the one provided by the manufacturer and used for Type Approval testing (hereinafter called "TA RL") by up to 30-70%, affecting accordingly fuel consumption and CO_2 emissions. This deviation between the two RLs is attributed to various reasons, such as different vehicle configuration, affecting aerodynamic resistance and weight, or different tires, affecting rolling resistance.

Coast-down testing was performed in a suitable test track with totally level road. Two sites were used for this testing: i) the runway of the airport of Thessaloniki (Figure 4), and ii) a public road driving to a dead end (Figure 5), without any traffic. Although that the former track is generally preferable, owing to the straight and level road, it was not always available. Therefore, it was necessary to have and use the latter site as an alternative. In addition, the test was conducted in both directions of the road, in order to eliminate any wind effects. All the procedures, such as vehicle preparation and test methodology, which were followed during the coast-down tests, complied with the prescriptions of the relevant Regulation UNECE R83, including wind speed.

Figure 4: The runway of the airport of Thessaloniki used for coast-down testing

Figure 5: The 2nd site used for coast-down testing

2.2.3 Laboratory Testing

With the realistic RL determined from the coast-down test, the laboratory tests were conducted on the chassis dyno of LAT (Figure 6). The typical test protocol is presented in Figure 7.

Figure 6: LAT chassis dyno (left) and chassis dyno control station (right)

Test details	Dyno Setting	Test Days		Dyno Setting	Test Days			Dyno Setting	Test Day
	Day S1	Day T1	Day T2	Day S2	Day T3	Day T4	Day T5	Day S3	Day T6
Inertia mass	Realistic inertia	Realistic inertia	Realistic inertia	Realistic inertia	Realistic inertia	Realistic inertia	Realistic inertia	TA inertia	TA inertia
Road load	Realistic RL	Realistic RL	Realistic RL	Realistic RL	Realistic RL	Realistic RL	Realistic RL	TA RL	TA RL
Test temperature	25°C	25°C	18°C	25°C	25°C	25°C	18°C	25°C	25°C
		—	—		Warm-up (Art. Urban)	—	—		—
Tests	coast-down for dyno setting with realistic road load and WLTC testing	cold WLTC	cold WLTC	coast-down for dyno setting with realistic road load and NEDC testing	Artemis Urban	cold NEDC	cold NEDC	coast-down for dyno setting with TA road load	cold NEDC
		coast-down	coast-down		—	coast-down	coast-down		coast-down
		bag analysis	bag analysis		bag analysis	bag analysis	bag analysis		bag analysis
		2 x EUDC	2 x EUDC		2 x EUDC	2 x EUDC	2 x EUDC		2 x EUDC
		hot WLTC	hot WLTC		Artemis Road	hot NEDC	hot NEDC		hot NEDC
		bag analysis	bag analysis		bag analysis	bag analysis	bag analysis		bag analysis
			2 x EUDC				2 x EUDC		
			Artemis Urban				Artemis Road		
			bag analysis				bag analysis		
	Controlled DPF regeneration (diesel)	Controlled DPF regeneration (diesel)		Controlled DPF regeneration (diesel)	Controlled DPF regeneration (diesel)	Controlled DPF regeneration (diesel)		Controlled DPF regeneration (diesel)	
Conditioning for next day	1 x WLTC	1 x WLTC		3 x EUDC (diesel) 1 x UDC + 2 x EUDC (gasoline)	3 x EUDC (diesel) 1 x UDC + 2 x EUDC (gasoline)	3 x EUDC (diesel) 1 x UDC + 2 x EUDC (gasoline)		3 x EUDC (diesel) 1 x UDC + 2 x EUDC (gasoline)	
Soak temperature for next day testing	25°C	18°C	25°C	25°C	25°C	18°C	25°C	25°C	
Comments	Battery charing over night	Battery charing over night	Battery charing over night	Battery charing over night	Battery charing over night	Battery charing over night	Battery charing over night	Battery charing over night	Battery charing over night

Figure 7: Typical test protocol for laboratory testing

In summary, laboratory testing included the following:

- WLTC, NEDC and Artemis tests with actual mass (derived by vehicle weighing without the driver) and road load.
- Tests at 25^{0}C, as well as at a lower temperature, typically 18^{0}C.
- NEDC tests with type approval mass and road load.
- WLTC and NEDC were tested both cold- and hot-started.
- After each cold-start cycle a coast-down on the chassis dyno was performed in order to verify that the RL did not deviate from the desired value.
- Before the hot-start cycle, a preconditioning procedure (consisting of 2 EUDCs) was applied in order to compensate for vehicle cooling during the coast-down and the bag analysis that followed after the cold-start cycle.
- In the case of diesel vehicles, a controlled DPF regeneration was performed in order to avoid such an event during a test and to start every test day with the same conditions, as concerns DPF loading. The regeneration was triggered and controlled with suitable diagnostic tools.
- The battery was charged overnight in order to start each day with the same state of charge and not to introduce an additional influencing parameter when studying, for example, the test temperature effect.
- For the WLTC gear shift strategy the Steven tool was used, version 6 May 2016.
- Emissions of gas pollutants: CO_2, CO, HC, NO/NO_x. From the bag values of gas pollutants fuel consumption will be also calculated.
- Particle mass (PM), with the filter paper method, and particle number (PN).

The analytical equipment available at LAT was employed for the measurements, which have been conducted according to the relevant regulations.

3 Results

All four vehicles were firstly tested in the "ThessTrip" and "ThessTrip Mountain" routes. For every vehicle, at least 2 valid "ThessTrip" repetitions were measured and 1 "ThessTrip Mountain" repetition. In some cases, additional measurements were conducted without OBD data recording. Each repetition of the RDE compliant measurement of the "ThessTrip" route is shortly referenced as "RDE". Each repetition of the dynamic driving pattern of the "ThessTrip Mountain" route is shortly referenced as "DYN".

The aggregated emission results (g/km) of the RDE tests are calculated using the Moving Average Window method (MAW) according to the current RDE regulation (Commission Regulation (EC) 2016/427 of 10 March 2016). Whereas, the aggregated emissions of the DYN tests, which are not RDE valid, are calculated simply as a division of the cumulative emission mass by the total driven distance.

Figure 8 and Figure 9 depict the measured velocity and altitude profile for the “ThessTrip” and “ThessTrip Mountain” routes respectively. All test repetitions with the four selected vehicles followed the same driving route and speed profiles. In Figure 8, the urban, rural and motorway parts of the RDE-compliant trip are clearly distinguished from the velocity pattern. The differences between the RDE-compliant and the dynamic (DYN) tests are clearly shown in these figures. The DYN route (Figure 9) includes driving in higher altitude, meaning uphill and downhill, characterised also by abrupt accelerations, without clear discrimination of urban, rural and motorway parts.

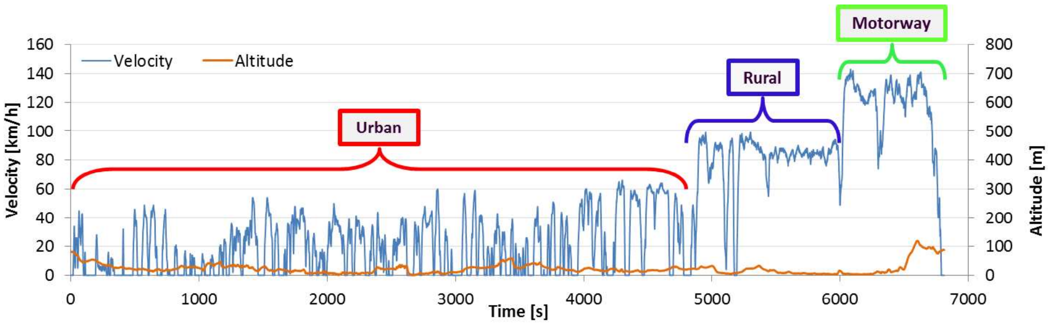


Figure 8: Vehicle velocity and altitude profile, following the RDE-compliant ThessTrip route

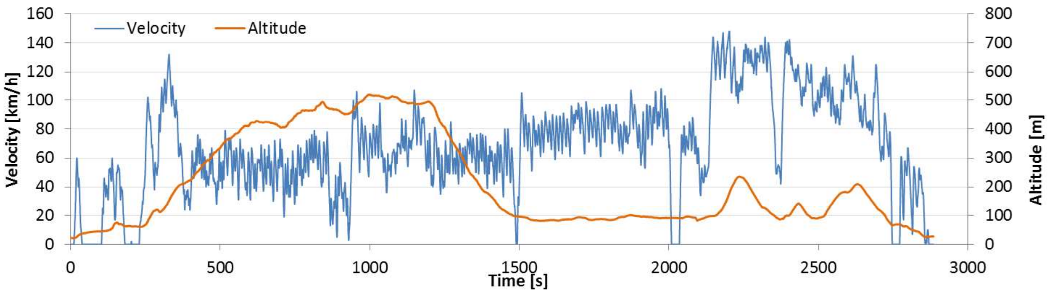
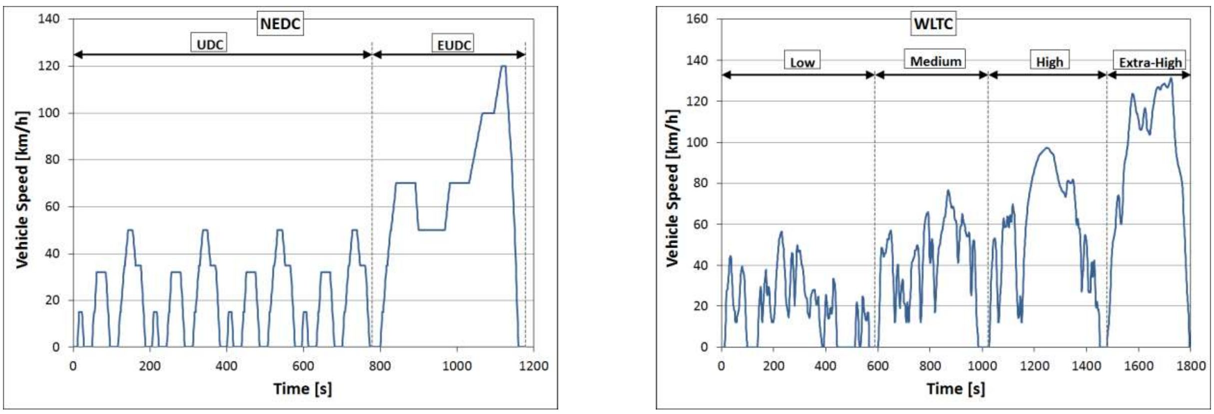


Figure 9: Vehicle velocity and altitude profile, following the Dynamic ThessTrip Mountain route

Concerning laboratory testing, Figure 10 presents the velocity profiles of the driving cycles tested. As stated, previously, both cold and hot start tests were conducted for NEDC and WLTC v5.3, under two different temperatures. The following sub-sections present the results for each vehicle, beginning with the on-road tests and continuing with the coast-down and the laboratory ones.



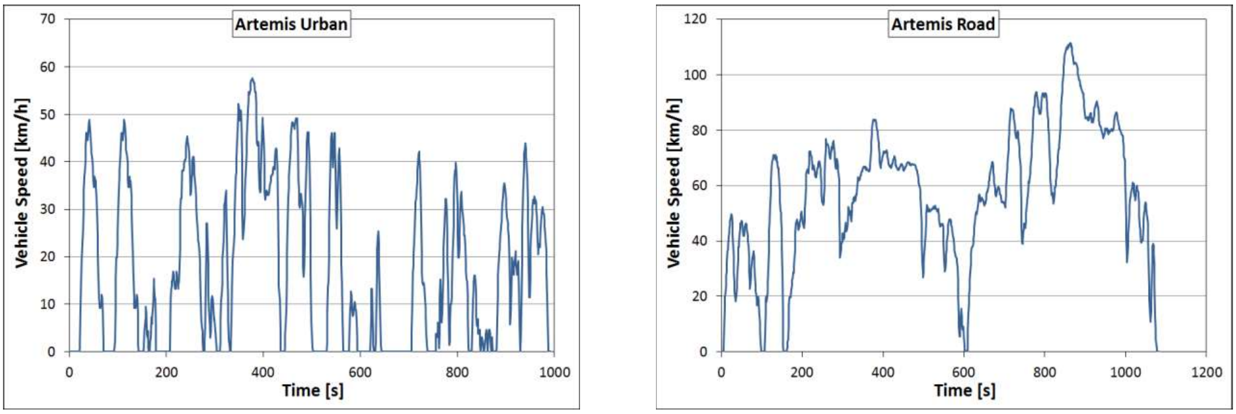


Figure 10: Vehicle speed profile for the driving cycles run in laboratory testing

3.1 Vehicle 1: BMW 520d

3.1.1 On-Road Testing

The BMW 520d was the first of the two vehicles equipped with LNT that were tested in the context of this study. The main technical specifications of this vehicle are presented in Table 4, while Table 5 summarizes the valid on-road tests conducted. Apart from the standard two RDE and one DYN tests, two additional were included, one RDE and one DYN, without any OBD recordings. Table 6 presents the ambient temperature during the on-road tests.

Table 4: BMW 520d technical specifications

MY & Chassis type	2015, Sedan
Engine	Diesel, 4-cyl
Drive & Transmission	RWD, Automatic
Number of gears	8
Max power [kW]	140
Engine capacity [cm^3]	1995
Start-stop	Yes
Euro class	6b
Aftertreatment system	DPF, LNT
Type approval CO_2 [g/km]	109
Mileage (start of testing) [km]	16,630

Table 5: BMW 520d test summary

Type of test	Number of tests
Standard RDE	2
Standard DYN	1
RDE without OBD	1
DYN without OBD	1

Table 7 summarizes the emissions for all the standard tests. It is noted that for the tests without OBD, it is not possible to calculate the emissions in mass values, as there are not any information concerning exhaust gas flow, while no correlation can be made with the standard tests (with OBD recordings), since driving conditions were not identical (e.g. traffic lights, interference with other vehicles etc.). However, no significant deviations have been observed in the instantaneous concentration values of emissions.

Table 8 presents the CO_2 emission results of all repetitions including the results of the three RDE parts. Slight differences are observed between the two RDE tests, while the dynamic driving in DYN1 test results in much higher CO_2 emissions (and fuel consumption, correspondingly). Table 9, in the same manner as Table 8, presents all NO_x emission results of all repetitions including the results of the three RDE parts. Again, some deviations are observed between the two RDE tests that are expected, since the LNT behaviour could not be identical and repeatable in the two tests. In the case of the DYN1 test, the difference is significant and it can be attributed to the higher engine speed and loads encountered in this test. Another factor contributing to the different NO_x emissions is the LNT regeneration events that took place during each test, as presented in Table 10. Although that the MAW method has not be applied in the DYN test, this is responsible only for a minor part (in the order of 3g/km CO_2) of the difference, whereas the distance between the RDE-compliant and the DYN tests is above 130g/km CO_2. Finally, Table 11 presents the average emissions of the three parts of the RDE-compliant tests, the average total emissions of the RDE-compliant tests and the total emissions of the DYN test.

Table 6: Ambient temperature during on-road testing

	BMW 520d		
	RDE 1	RDE 2	DYN 1
min	13.3	9.3	11.2
max	16.6	11.2	22.5
average	14.0	10.3	14.3

Table 7: Total trip emissions for all repetitions

All emissions, MAW method except DYN 1			
	RDE 1	RDE 2	DYN 1
CO_2 [g/km]	153.6	161.4	289.9
NO_x [mg/km]	331.7	461.5	3218.0
CO [mg/km]	1.6	5.1	13.0
NO [mg/km]	228.1	314.7	2270.1
NO_2 [mg/km]	103.7	146.8	947.9

Table 8: CO_2 emissions of the total trip and the urban, rural, motorway parts

CO_2 [g/km], MAW method except DYN 1			
	RDE 1	RDE 2	DYN 1
Urban	171.8	180.0	
Rural	136.7	148.3	
Motorway	151.8	155.4	
Total	153.6	161.4	289.9

Table 9: NO_x emissions of the total trip and the urban, rural, motorway parts

NO_x [mg/km], MAW method except DYN 1			
	RDE 1	RDE 2	DYN 1
Urban	232.8	302.1	
Rural	434.1	530.8	
Motorway	331.4	556.5	
Total	331.7	461.5	3218.0

Table 10: LNT regenerations during each test

LNT [#]	RDE 1		RDE 2, no S-S		DYN 1	
	LNT Regeneration	NO_x [mg/km]	LNT Regeneration	NO_x [mg/km]	LNT Regeneration	NO_x [mg/km]
Urban	3	233	2	302		
Rural	3	434	2	531		
Motorway	2	331	2	556		
Total	8	332	6	462	0	3218

Table 11: Average emissions of RDE trips and DYN trips

Average of RDE 1-RDE 2 and DYN 1					
	CO_2 [g/km]	NO_x [mg/km]	CO [mg/km]	NO [mg/km]	NO_2 [mg/km]
RDE Urban	175.9	267.4	4.4	176.3	91.1
RDE Rural	142.5	482.4	1.6	324.8	157.6
RDE Motorway	153.6	444.0	4.0	315.9	128.0
RDE Total	157.5	396.6	3.4	271.4	125.2
DYN Total	289.9	3218.0	13.0	2270.1	947.9

Figure 11 and Figure 12 illustrate the instantaneous CO_2 and NO_x mass flows during the RDE2 and the DYN1 test respectively. The much more dynamic driving style and speed profile of the DYN1 test causes significantly higher average emissions (both CO_2 and NO_x) than regular driving and much higher peak values, too.

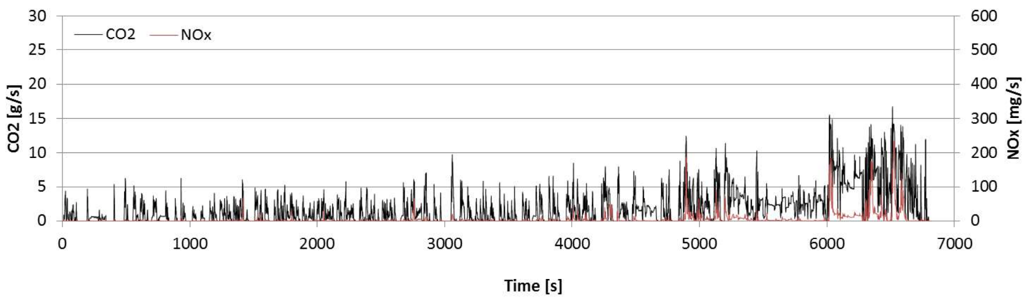


Figure 11: Instantaneous CO_2 and NO_x emissions mass flow during the RDE2 test

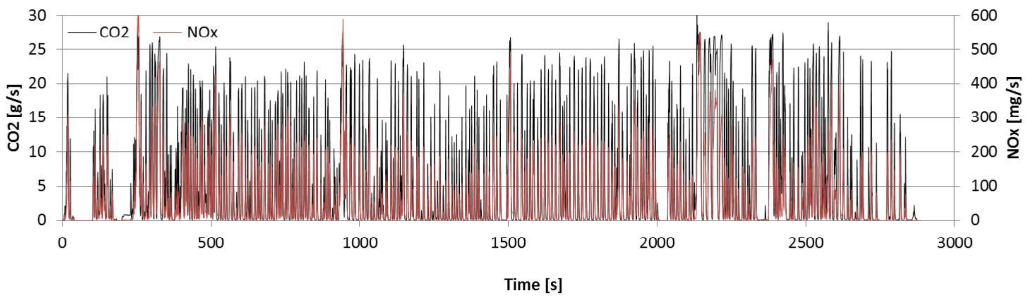


Figure 12: Instantaneous CO_2 and NO_x emissions mass flow during the DYN1 test

The on-road test results of the BMW 520d concluded to 158±4 gCO_2/km following a regular RDE-compliant driving profile and 290 gCO_2/km following a dynamic driving profile. Also, following the RDE-compliant route, the average NO_x exceedance factor (EF, i.e. the ratio of measured emissions divided by the respective limit) was 5±0.8 for the total trip and 3.3±0.4 for the urban part. The respective EF for NO_x in the dynamic route was 40, as also shown in Table 12.

Finally, as regards vehicle driving dynamics, the RDE-compliant trips were found within the legislation limits, while the dynamic ones where significantly above the limit. Specifically, Figure 13 presents the average v*a parameter for urban, rural and motorway parts of the RDE-compliant and DYN trips.

Table 12: Average exceedance factors for the measured tests

EF	NO_x
RDE Urban	3.3 ± 0.4
RDE Total	5 ± 0.8
DYN Total	40

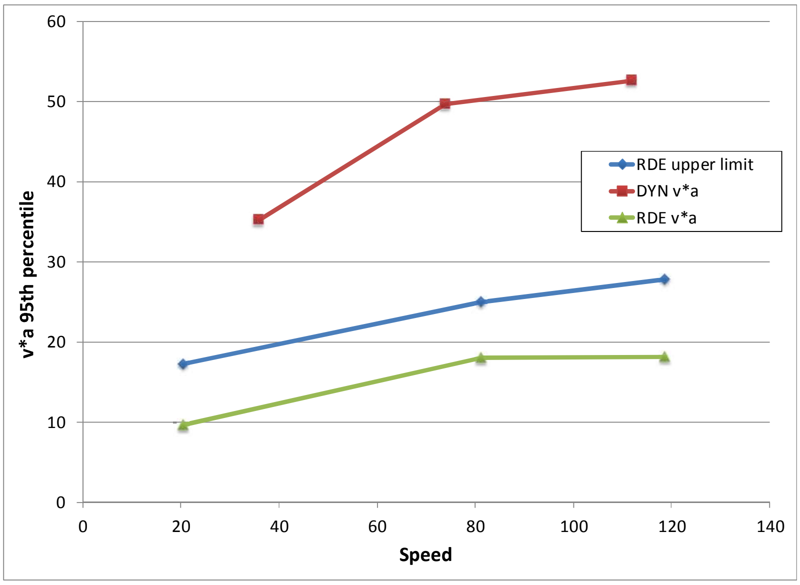


Figure 13: Average v*a 95th percentile for the RDE-compliant and the dynamic trips

3.1.2 Coast-down and Laboratory Testing

Before running the laboratory tests, a coast-down was conducted in order to determine the realistic road load of the vehicle, to be used on the chassis dyno measurements. Table 13 presents the realistic coast-down time together with the NEDC and WLTP-H ones (the respective road loads provided by the manufacturer). It is observed that the final realistic coast-down time is very close to the WLTP-H one, however this does not necessarily mean that the corresponding coast-down curves are the same. Compared to the NEDC coast-down time, the realistic one deviates significantly, about 80 sec.

Table 13: Coast-down times

Conditions	Coast-down time [s]
NEDC	261
WLTP-High	179
Realistic	179

For the faultless operation of the vehicle on the dyno, as well as for assuring the same testing conditions every day, the following actions were taken:

- The dyno mode of the vehicle was applied, following a specific procedure. This was necessary, since the vehicle was tested on a 1-axis chassis dyno.
- A controlled DPF regeneration took place at the end of each testing day in order on the one hand to avoid such an event during a driving cycle and on the other to ensure the same conditions at the beginning of each day.

Table 14 summarizes the emission and fuel consumption results of the chassis dyno measurements. All tests were conducted at 25ºC, as the typical temperature for NEDC testing, and were repeated at a lower temperature, around 19-20ºC. NEDC was tested with both realistic and type approval road load, the latter just to confirm the normal operation of the vehicle. In addition, the Artemis Road test at the lower temperature, failed due to a DPF regeneration, was repeated. A very good repeatability is confirmed from the results in Table 14.

Table 14: Chassis dyno results for the BMW 520d

Driving Cycle	Start	Comment	Road Load	Temperature (ºC)	CO_2 [g/km]	CO [g/km]	HC [g/km]	NO_x [g/km]	NO [g/km]	FC [l/100 km]	PM [mg/km]
NEDC	Cold		Real World	25	131.5	0.025	0.022	0.032	0.019	4.98	0.32
	Cold		Real World	19	136.8	0.052	0.019	0.025	0.016	5.18	0.57
	Cold		Real World	19	137.0	0.064	0.016	0.035	0.021	5.19	0.19
	Cold		Type Approval	25	117.5	0.034	0.018	0.039	0.024	4.45	0.49
	Cold		Type Approval	25	118.8	0.035	0.013	0.038	0.021	4.50	0.19
	Hot		Real World	25	126.0	0.010	0.013	0.081	0.041	4.77	0.39
	Hot		Real World	20	130.6	0.008	0.016	0.068	0.037	4.95	0.22
	Hot		Real World	19	130.1	0.007	0.015	0.060	0.032	4.93	0.09
	Hot		Type Approval	25	115.9	0.022	0.015	0.059	0.031	4.39	0.09
WLTC	Cold		Real World	25	133.5	0.017	0.017	0.076	0.032	5.06	0.22
	Cold		Real World	19	135.6	0.023	0.021	0.096	0.044	5.14	0.08
	Hot		Real World	25	134.2	0.013	0.013	0.151	0.060	5.08	0.13
	Hot		Real World	20	132.4	0.012	0.018	0.112	0.051	5.02	0.11
Artemis	Urban (cold)	Warm-up cycle	Real World	25	223.2	0.000	0.000	0.150	0.076	8.45	0.00
	Urban (hot)		Real World	20	221.3	0.011	0.000	0.187	0.093	8.38	0.26
	Urban (hot)		Real World	25	216.8	0.018	0.000	0.316	0.139	8.21	0.48
	Road		Real World	25	119.9	0.011	0.005	0.476	0.154	4.54	0.94
	Road	DPF regeneration	Real World	20	171.1	0.010	0.011	0.739	0.297	6.48	2.11
	Road		Real World	19	122.2	0.004	0.008	0.506	0.177	4.63	0.19
	Road		Real World	25	122.3	0.005	0.004	0.514	0.187	4.63	0.13

Figure 14 presents the CO_2 emission results for the NEDC tests, both cold and hot. Both temperature and road load effects are observed in these results. Taking as basis the value with realistic road load at 25ºC, the lower test temperature caused higher CO_2 emissions by 5.5 and 4.4 g/km in cold and hot cycle, respectively, while the higher (realistic) road load resulted in 13.4 and 10.1 g/km difference in cold and hot cycle, respectively. In the other test cycles, these effects are not that prominent. In WLTC, the CO_2 emission results seem not to be differentiated significantly between cold and hot start, and this is attributed to the different gear shift strategy followed by the automatic transmission of the vehicle. In the case of Artemis Urban cycle, the lower test temperature resulted in 4.5 g/km higher CO_2 emissions.

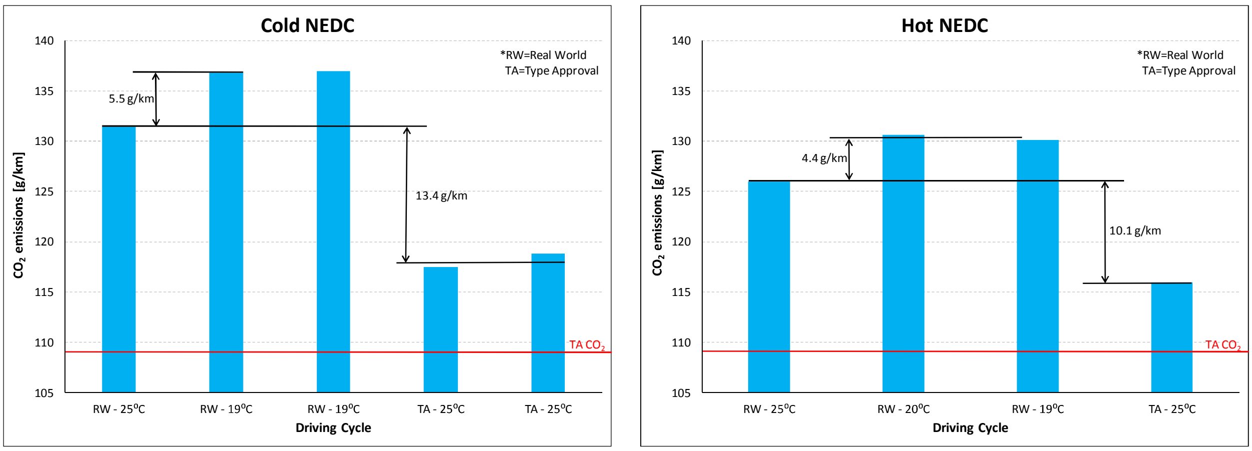


Figure 14: CO_2 emissions in cold NEDC (left) and hot NEDC (right)

Figure 15 presents the NO_x emission results for the NEDC tests, both cold and hot. In all cases, independently of test temperature and road load, the results are below the Euro 6 limit, and are in the range of 25-40 mg/km. However, the actual effect of temperature and road load is not clearly revealed, due to the presence of LNT – a different cleaning strategy might be followed, both during the test cycle as well as during the preconditioning procedure, affecting the LNT condition at the beginning of the tests.

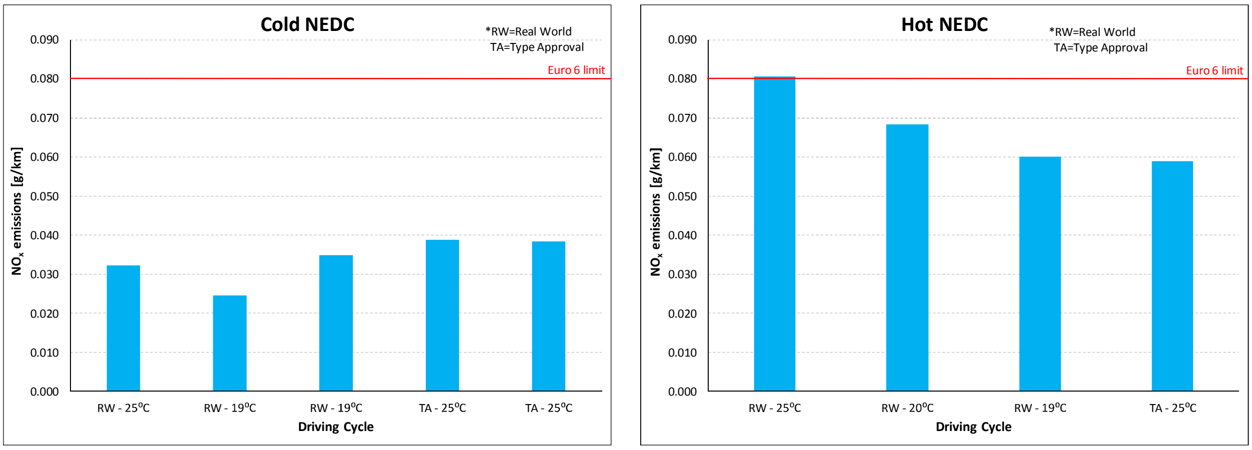


Figure 15: NO_x emissions in cold NEDC (left) and hot NEDC (right)

3.2 Vehicle 2: Nissan Pulsar

3.2.1 On-Road Testing

The Nissan Pulsar was the second vehicle equipped with LNT tested in the context of this study. The main technical specifications of this vehicle are presented in Table 15, while Table 16 summarizes the valid on-road tests conducted. In total, three RDE-compliant and two dynamic tests were conducted, together with another RDE-compliant one without Start-Stop – the last step was performed intentionally without Start-Stop, since this function was not operational on the chassis dyno. Table 17 presents the ambient temperature during the on-road tests.

Table 15: Nissan Pulsar technical specifications

MY & Chassis type	2016, Hatchback
Engine	Diesel, 4-cyl
Drive & Transmission	FWD, Manual
Number of gears	6
Max power [kW]	81
Engine capacity [cm^3]	1461
Start-stop	Yes
Euro class	6
Aftertreatment system	DOC, DPF, LNT
Type approval CO_2 [g/km]	94
Mileage (start of testing) [km]	27,540

Table 16: Nissan Pulsar test schedule

Type of test	Number of tests
Standard RDE	3
Standard DYN	2
RDE without Start-Stop	1

Table 17: Ambient temperature during on-road testing

	Nissan Pulsar					
	RDE1	RDE2	RDE3	RDE4	DYN1	DYN2
min	6.5	10.8	12.5	11.8	4.5	4.1
max	10.7	12.7	15.3	16.5	9.3	8.6
average	9.2	11.7	13.7	15.0	7.3	6.8

Table 18 summarizes the emissions for all the tests. A high variability of CO_2 emissions is observed, something that can be expected in on-road tests. The main conclusion here is that Start-Stop does not seem to result in great reduction of CO_2 emissions under real driving conditions. Table 19 presents the CO2 emission results of all repetitions including the results of the three RDE parts. Table 20, in the same manner as Table 19, presents all NO_x emission results of all repetitions including the results of the three RDE parts. Similar values are observed for all the RDE-compliant tests – again some deviations are observed, since the LNT behaviour could not be the same and repeatable in all the tests. In the case of the dynamic tests, the difference is significant and it is clearly attributed to the higher engine speed and loads considered in these tests. Another factor contributing to the different NO_x emissions is the LNT regeneration events that took place during each test, as presented in Table 21. Finally, Table 22 presents the average emissions of the three parts of the RDE-compliant tests, the average total emissions of the RDE-compliant tests and the total emissions of the DYN test.

Table 18: Total trip emissions for all repetitions

All emissions, MAW method except DYN 1 & DYN 2						
	RDE 1	RDE 2, no S-S	RDE 3	RDE 4	DYN 1	DYN 2
CO_2 [g/km]	122.9	120.4	127.0	131.5	190.1	178.2
NO_x [mg/km]	1314.8	1294.7	1340.7	1296.0	2200.2	1928.7
CO [mg/km]	28.7	1.7	23.2	5.2	9.5	29.6
NO [mg/km]	877.2	878.0	898.3	841.5	1673.5	1459.6
NO_2 [mg/km]	437.5	416.7	442.4	454.4	526.7	469.1

Table 19: CO_2 emissions of the total trip and the urban, rural, motorway parts

CO_2 [g/km], MAW method except DYN 1 & DYN 2						
	RDE 1	RDE 2, no S-S	RDE 3	RDE 4	DYN 1	DYN 2
Urban	129.5	122.6	133.6	141.4		
Rural	105.4	103.2	107.0	106.8		
Motorway	133.7	135.6	140.1	146.0		
Total	122.9	120.4	127.0	131.5	190.1	178.2

Table 20: NO_x emissions of the total trip and the urban, rural, motorway parts

NO_x [mg/km], MAW method except DYN 1 & DYN 2						
	RDE 1	RDE 2, no S-S	RDE 3	RDE 4	DYN 1	DYN 2
Urban	1269.0	1079.9	1000.9	1038.3		
Rural	1206.5	1171.3	1196.8	1140.8		
Motorway	1470.1	1639.2	1834.8	1716.7		
Total	1314.8	1294.7	1340.7	1296.0	2200.2	1928.7

Table 21: LNT regenerations during each test

LNT [#]	RDE 1		RDE 2, no S-S		RDE 3		RDE 4	
	LNT Regen	NOx [mg/km]	LNT Regen	NOx [mg/km]	LNT Regen	NOx [mg/km]	LNT Regen	NOx [mg/km]
Urban	1	1269	1	1080	1	1001	2	1038
Rural	2	1207	4	1171	1	1197	4	1141
Motorway	6	1470	3	1639	1	1835	3	1717
Total	9	1315	8	1295	3	1341	9	1296

LNT [#]	DYN 1		DYN 2	
	LNT Regen	NOx [mg/km]	LNT Regen	NOx [mg/km]
Urban				
Rural				
Motorway				
Total	1	2200	3	1929

Table 22: Average emissions of RDE trips and DYN trips

Average of RDE 1-RDE 4 and DYN 1-DYN 2					
	CO_2 [g/km]	NO_x [mg/km]	CO [mg/km]	NO [mg/km]	NO_2 [mg/km]
RDE Urban	131.8	1097.0	29.2	825.2	271.9
RDE Rural	105.6	1178.9	8.8	765.2	413.7
RDE Motorway	138.8	1665.2	5.6	1032.5	632.7
RDE Total	125.4	1311.5	14.7	873.8	437.8
DYN Total	184.2	2064.4	19.6	1566.6	497.9

Figure 16 and Figure 17 illustrate the instantaneous CO_2 and NO_x mass flows during the RDE 1 test and DYN 1 test respectively. The much more dynamic driving style and speed profile of the DYN 1 test causes higher average emissions (both CO_2 and NO_x) than regular driving and much higher peak emission values.

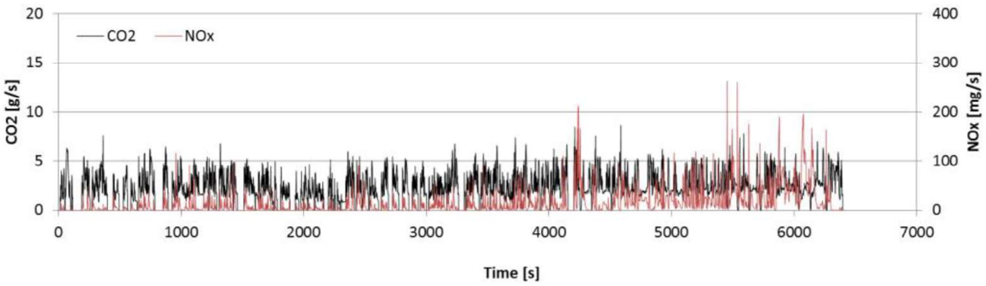


Figure 16: Instantaneous CO_2 and NO_x emissions mass flow during the RDE 1 test.

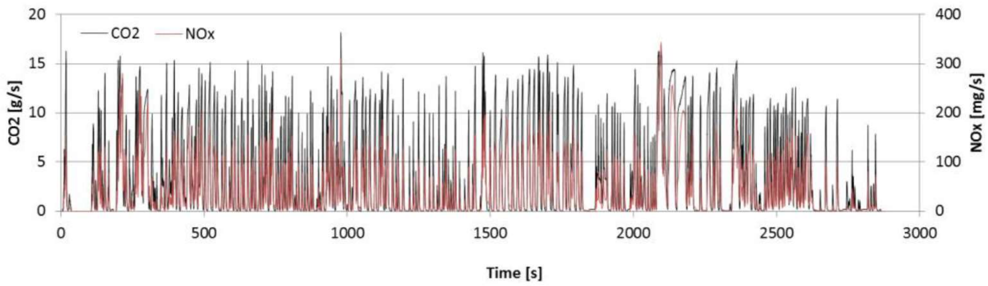


Figure 17: Instantaneous CO_2 and NO_x emissions mass flow during the DYN 1 test.

The on-road test results of the Nissan Pulsar concluded to 125±6 gCO_2/km following a regular RDE-compliant driving profile and 184±6 gCO_2/km following a dynamic driving profile. Also, following the RDE-compliant route, the average NO_x exceedance factor (EF) was 16.4±0.3 for the total trip and 13.7±2 for the urban part. The respective EF for NO_x in the dynamic route was 26±1.5, as also shown in Table 23. Finally, as regards vehicle driving dynamics, the RDE-compliant trips were found within the legislation limits, while the dynamic ones where significantly above the limit. Specifically, Figure 18 presents the average v*a parameter for urban, rural and motorway parts of the RDE-compliant and DYN trips.

Table 23: Average exceedance factors for the measured tests

EF	NO_x
RDE Urban	13.7 ± 2
RDE Total	16.4 ± 0.3
DYN Total	26 ±1.5

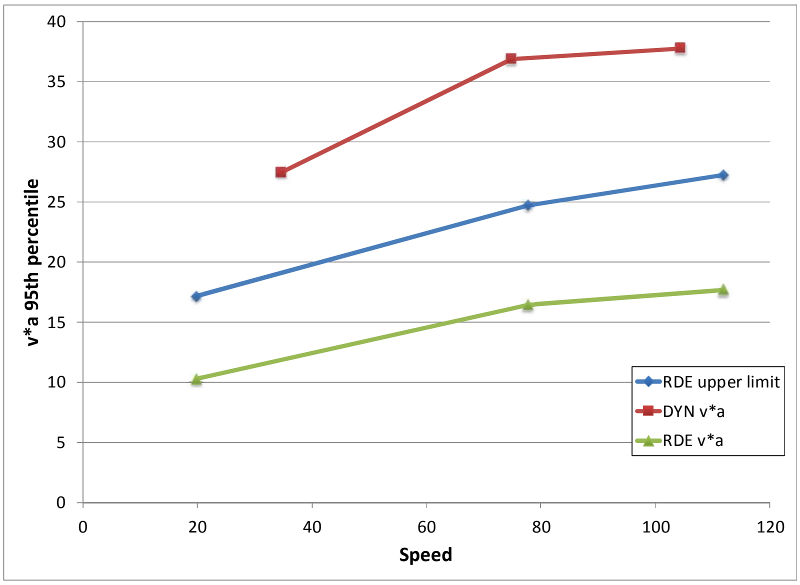


Figure 18: Average v*a 95th percentile for the RDE-compliant and the dynamic trips

3.2.2 Coast-down and Laboratory Testing

Before running the laboratory tests, a coast-down was conducted in order to determine the realistic road load of the vehicle, to be used on the chassis dyno measurements. Table 24 presents the realistic coast-down time together with the NEDC one (the respective road load provided by the manufacturer). It is observed that the final realistic coast-down time is lower than the respective of NEDC, with the deviation reaching 70 sec.

Table 24: Coast-down times

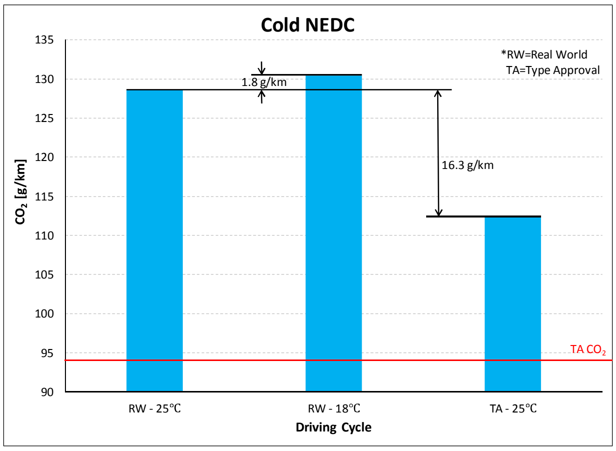
Conditions	Coast-down time [s]
NEDC	279
Realistic	207

During the chassis dyno measurements, a controlled DPF regeneration took place at the end of each testing day in order on the one hand to avoid such an event during a driving cycle and on the other to ensure the same conditions at the beginning of each day. In addition, Start-Stop was not operational during the chassis-dyno testing, owing to the inability to set the vehicle into "dyno mode" (a connection to the CAN bus was required) – however, no any other malfunctions were experienced. Table 25 summarizes the emission and fuel consumption results of the chassis dyno measurements. All tests were conducted at 25ºC, as the typical temperature for NEDC testing, and were repeated at a lower temperature, around 18ºC. NEDC was tested with both realistic and type approval road load, the latter just to confirm the normal operation of the vehicle.

Table 25: Chassis dyno results for the Nissan Pulsar

Driving Cycle	Start	Road Load	Temperature (ºC)	CO_2 [g/km]	CO [g/km]	HC [g/km]	NOx [g/km]	NO [g/km]	FC [l/100 km]
NEDC	Cold	Real world	25	128.7	0.078	0.010	0.340	0.141	4.88
	Cold	Real world	18	130.5	0.132	0.014	0.284	0.142	4.95
	Cold	Type approval	25	112.4	0.046	0.016	0.133	0.075	4.26
	Hot	Real world	25	118.1	0.013	0.016	1.379	0.496	4.48
	Hot	Real world	18	118.1	0.018	0.014	0.533	0.242	4.47
	Hot	Type approval	25	100.1	0.004	0.032	0.934	0.411	3.80
WLTC	Cold	Real world	25	124.1	0.019	0.006	0.625	0.198	4.70
	Cold	Real world	18	125.4	0.030	0.018	0.543	0.183	4.75
	Hot	Real world	25	117.7	0.010	0.006	1.281	0.337	4.46
	Hot	Real world	18	119.4	0.004	0.007	0.643	0.213	4.52
Artemis	Urban (hot)	Real world	18	193.0	0.027	0.009	1.603	0.660	7.31
	Urban (hot)	Real world	25	197.6	0.000	0.010	2.199	0.868	7.48
	Road	Real world	25	116.5	0.004	0.004	1.109	0.370	4.41
	Road	Real world	18	116.1	0.000	0.009	0.563	0.218	4.40

Figure 19 presents the CO_2 emission results for the NEDC tests, both cold and hot. Both temperature and road load effects are observed in these results. The decrease of test temperature by 7ºC resulted in 1.8 g/km increase of CO_2 emissions. Furthermore, the difference in CO_2 emissions between cold NEDC with real world and cold NEDC with type approval road load was 16.3 g/km. The same comparison is held with hot NEDC CO_2 emissions. The difference between the test with real world and type approval road load located at the same level as for cold NEDC, i.e. 18 g/km. In WLTC and Artemis cycles, the effect of test temperature on CO_2 emissions seems not that prominent.



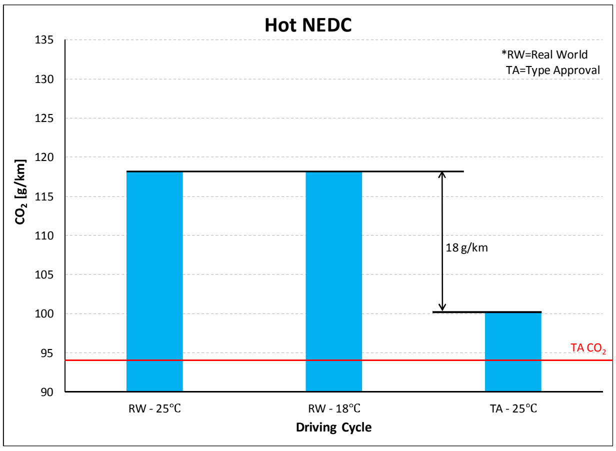


Figure 19: CO_2 emissions in cold NEDC (left) and hot NEDC (right)

Figure 20 presents the NO_x emission results for the NEDC tests, both cold and hot. In all the tested cycles, the results were above the Euro 6 limit, with higher emissions observed for the cases of realistic road load. In the hot-started cycles, NO_x emissions were much higher and this can be attributed to the different EGR strategy followed in some cases, as revealed in Figure 21. The specific vehicle presents very high NO_x emissions in all cycles, as observed in Table 25.

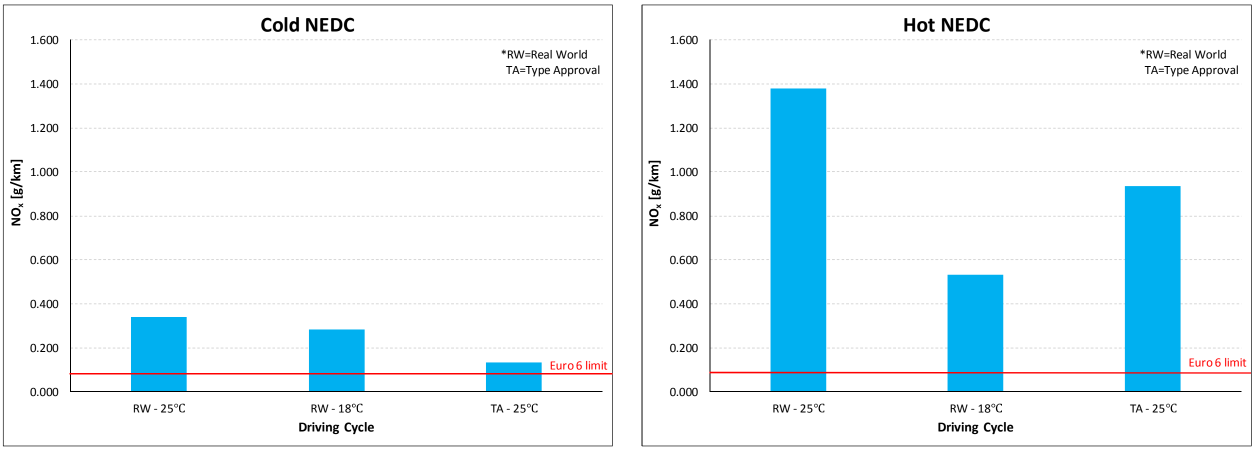


Figure 20: NO_x emissions in cold NEDC (left) and hot NEDC (right)

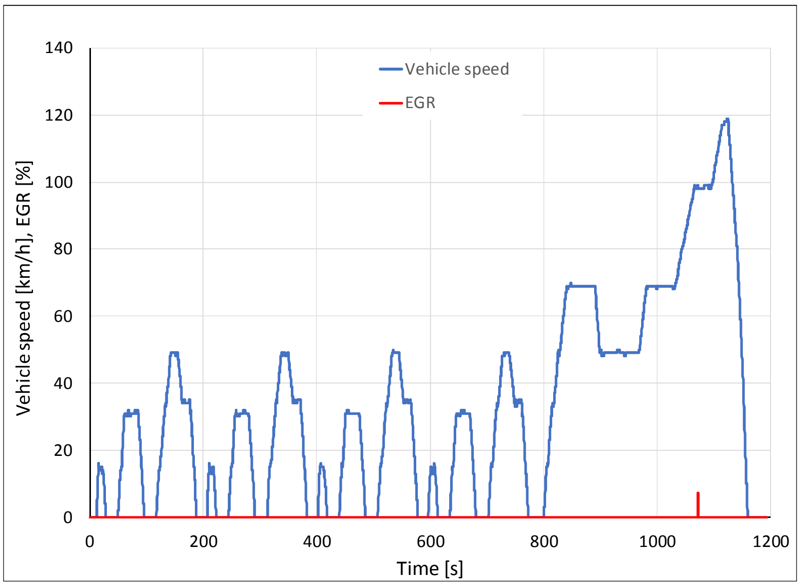


Figure 21: EGR rate during a hot NEDC

3.3 Vehicle 3: Opel Insignia

3.3.1 On-Road Testing

The Opel Insignia was the third diesel vehicle tested in the context of this study, equipped with SCR. The main technical specifications of this vehicle are presented in Table 26, while Table 27 summarizes the valid on-road tests conducted. In total, two RDE-compliant and two dynamic tests were conducted, together with another RDE-compliant without Start-Stop and an additional one without OBD. Table 28 presents the ambient temperature during the on-road tests.

Table 26: Opel Insignia technical specifications

MY & Chassis type	2016, Station wagon
Engine	Diesel, 4-cyl
Drive & Transmission	FWD, Manual
Number of gears	6
Max power [kW]	125
Engine capacity [cm^3]	1956
Start-stop	Yes
Euro class	6
Aftertreatment system	DOC, DPF, SCR
Type approval CO_2 [g/km]	124
Mileage (start of testing) [km]	20,560

Table 27: Opel Insignia test schedule

Type of test	**Number of tests**
Standard RDE	2
Standard DYN	2
RDE without Start-Stop	1
RDE without OBD	1

Table 28: Ambient temperature during on-road testing

	Opel Insignia					
	RDE1	RDE2	RDE3	RDE4, no OBD	DYN1	DYN2
min	11.7	9.6	18.5	16.8	9.0	10.1
max	15.9	14.4	24.4	23.3	20.7	15.7
average	13.2	12.5	20.8	20.1	12.6	12.7

Table 29 summarizes the emissions for all the tests. It is noted that for the tests without OBD, it is not possible to calculate the emissions in mass values, as there are not any information concerning exhaust gas flow, while no correlation can be made with the standard tests (with OBD recordings), since driving conditions were not identical (e.g. traffic lights, interference with other vehicles etc.). However, no significant deviations have been observed in the instantaneous concentration values of emissions.

Beginning with CO_2 emissions, it is observed that the two standard RDE tests (1 & 2) present very similar values, while RDE3, the one without Start-Stop, exhibits higher values, with the main difference being in the Urban part, as can be seen in the analysis of Table 30. On the other hand, RDE3 presents lower NO_x emissions (Table 29), with the main difference now being at the Rural and Motorway parts, as revealed in Table 31. In all cases, the dynamic tests present significantly higher values in both CO_2 and NO_x emissions, owing clearly attributed to the higher engine speed and loads considered in this test. Finally, Table 32 presents the average emissions of the three parts of the RDE-compliant tests, the average total emissions of the RDE-compliant tests and the average total emissions of the DYN test.

Table 29: Total trip emissions for all repetitions

All emissions, MAW method except DYN1 & DYN2					
	RDE 1	RDE 2	RDE 3, no S-S	DYN 1	DYN 2
CO_2 [g/km]	155.5	152.2	162.2	256.3	245.0
NO_x [mg/km]	895.1	877.8	613.9	2119.1	2074.8
CO [mg/km]	10.3	53.5	57.2	63.2	83.4
NO [mg/km]	568.1	486.2	327.1	1396.6	1377.2
NO_2 [mg/km]	326.9	391.6	286.8	722.5	697.6

Table 30: CO_2 emissions of the total trip and the urban, rural, motorway parts

CO_2 [g/km], MAW method except DYN1 & DYN2					
	RDE 1	RDE 2	RDE 3, no S-S	DYN 1	DYN 2
Urban	174.3	164.9	188.1		
Rural	135.0	130.7	137.5		
Motorway	156.6	160.5	160.2		
Total	155.5	152.2	162.2	256.3	245.0

Table 31: NO_x emissions of the total trip and the urban, rural, motorway parts

NO_x [mg/km], MAW method except DYN1 & DYN2					
	RDE 1	RDE 2	RDE 3, no S-S	DYN 1	DYN 2
Urban	1330.2	1134.7	1167.4		
Rural	558.5	580.5	137.6		
Motorway	783.3	910.3	520.0		
Total	895.1	877.8	613.9	2119.1	2074.8

Table 32: Average emissions of RDE trips and DYN trips

Average of RDE1-RDE3 and DYN1-DYN2					
	CO_2 [g/km]	NO_x [mg/km]	CO [mg/km]	NO [mg/km]	NO_2 [mg/km]
RDE Urban	175.8	1210.8	85.4	764.8	445.9
RDE Rural	134.4	425.6	27.0	221.7	203.8
RDE Motorway	159.1	737.9	7.4	385.6	352.2
RDE Total	156.6	795.6	40.4	460.5	335.1
DYN Total	250.7	2096.9	73.3	1386.9	710.1

Figure 22 and Figure 23 illustrate the instantaneous CO_2 and NO_x mass flows during the RDE 1 test and DYN 1 test respectively. The much more dynamic driving style and profile of the DYN 1 test causes higher average emissions (both CO_2 and NO_x) than regular driving and much higher peak emission values.

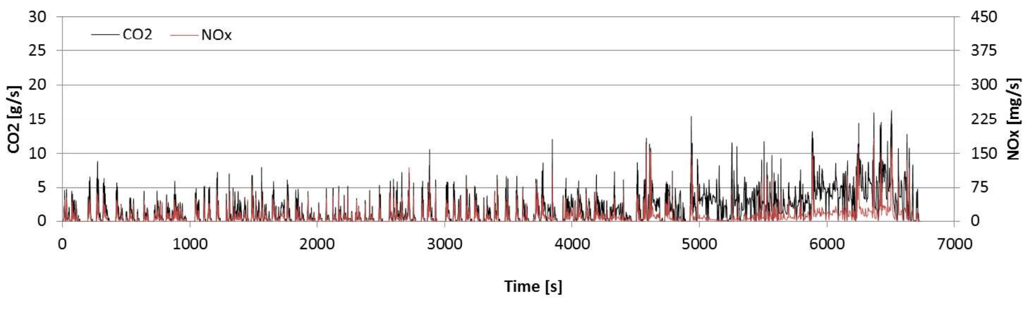


Figure 22: Instantaneous CO_2 and NO_x emissions mass flow during the RDE 1 test.

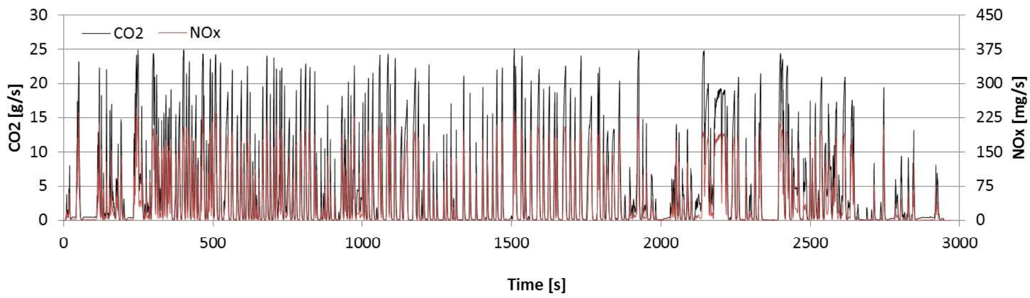


Figure 23: Instantaneous CO_2 and NO_x emissions mass flow during the DYN 1 test.

The on-road test results of the Opel Insignia concluded to 157±5 gCO_2/km following the RDE-compliant driving profile and 251±6 gCO_2/km following a dynamic driving profile. Also, following the RDE-compliant route, the average NO_x exceedance factor (EF) was 10±2.3 for the total trip and 15±1.5 for the urban part. The respective EF for NO_x in the dynamic route was 26.2±0.3, as also shown in Table 33. Finally, as regards vehicle driving dynamics, the RDE-compliant trips were found within the legislation limits, while the dynamic ones where significantly above the limit. Specifically, Figure 24 presents the average v*a parameter for urban, rural and motorway parts of the RDE-compliant and DYN trips.

Table 33: Average exceedance factors for the measured tests

EF	NO_x
RDE Urban	15 ± 1.5
RDE Total	10 ± 2.3
DYN Total	26.2 ± 0.3

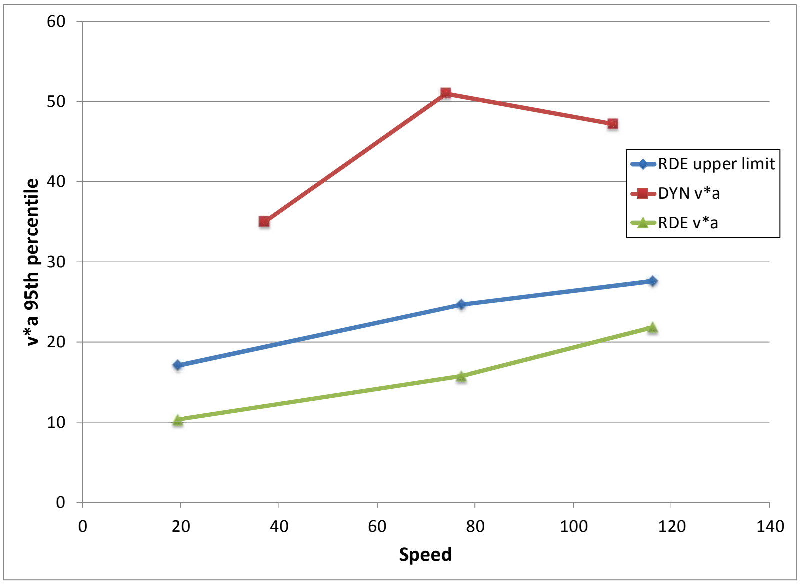


Figure 24: Average v*a 95th percentile for the RDE-compliant and the dynamic trips

3.3.2 Coast-down and Laboratory Testing

Before running the laboratory tests, a coast-down was conducted in order to determine the realistic road load of the vehicle, to be used on the chassis dyno measurements. Table 34 presents the realistic coast-down time together with the NEDC and WLTP-H ones (the respective road loads provided by the manufacturer). It is observed that the final realistic coast-down time is lower than both the NEDC and the WLTP-H ones, presenting a deviation of 96 sec with the former and 43 sec with the latter.

Table 34: Coast-down times

Conditions	Coast-down time [s]
NEDC	244
WLTP-High	191
Realistic	148

During the chassis dyno measurements, a controlled DPF regeneration took place at the end of each testing day in order on the one hand to avoid such an event during a driving cycle and on the other to ensure the same conditions at the beginning of each day. Table 35 summarizes the emission and fuel consumption results of the chassis dyno measurements. All tests were conducted at 25°C, as the typical temperature for NEDC testing, and were repeated at a lower temperature, around 18°C. NEDC was tested with both realistic and type approval road load, the latter just to confirm the normal operation of the vehicle.

Table 35: Chassis dyno results for the Opel Insignia

Driving Cycle	Start	Road Load	Temperature (°C)	CO_2 [g/km]	CO [g/km]	HC [g/km]	NOx [g/km]	NO [g/km]	FC [l/100 km]
NEDC	Cold	Real World	25	170.3	0.096	0.011	0.120	0.060	6.45
	Cold	Real World	18	175.3	0.141	0.022	0.110	0.055	6.65
	Cold	Type approval	25	147.6	0.091	0.003	0.095	0.051	5.59
	Hot	Real World	25	155.9	0.005	0.000	0.038	0.024	5.90
	Hot	Real World	18	158.8	0.007	0.000	0.024	0.014	6.01
	Hot	Type Approval	25	133.8	0.001	0.000	0.052	0.031	5.07
WLTC	Cold	Real World	25	157.8	0.171	0.004	0.336	0.100	5.98
	Cold	Real World	18	159.3	0.127	0.004	0.228	0.072	6.04
	Hot	Real World	25	154.3	0.050	0.000	0.087	0.020	5.84
	Hot	Real World	18	153.9	0.026	0.001	0.094	0.024	5.83
Artemis	Urban (hot)	Real World	18	264.8	0.398	0.000	0.110	0.057	10.05
	Urban (hot)	Real World	25	259.8	0.420	0.000	0.482	0.157	9.86
	Road	Real World	25	157.2	0.006	0.001	0.082	0.047	5.95
	Road	Real World	18	156.7	0.005	0.000	0.056	0.033	5.93

Figure 25 presents the CO_2 emission results for the NEDC tests, both cold and hot. Both temperature and road load effects are observed in these results. The decrease of test temperature by 7°C resulted in 5.1 g/km increase of CO_2 emissions. Furthermore, the difference in CO_2 emissions between cold NEDC with real world and cold NEDC with type approval road load was 22.7 g/km. The same comparison is held with hot NEDC CO_2 emissions results showing the same outcome as for the cold NEDC. The decrease of test temperature by 7°C resulted in 2.9 g/km CO_2 emissions increase with the difference between the test with real world and type approval road load located, at the same level as for cold NEDC, i.e. 22.1 g/km. In WLTC and Artemis cycles, the effect of test temperature on CO_2 emissions seems not that prominent.

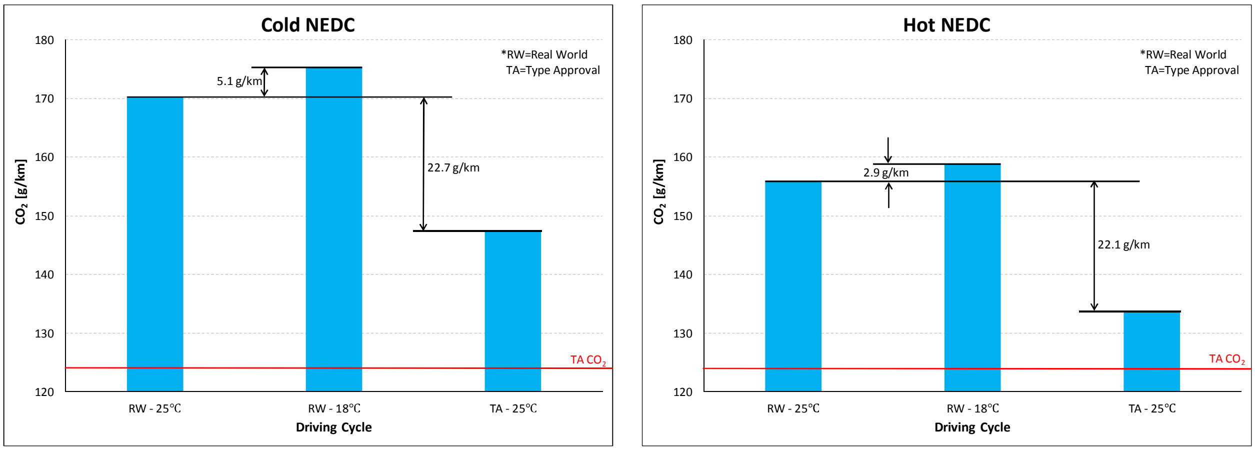


Figure 25: CO_2 emissions in cold NEDC (left) and hot NEDC (right)

Figure 26 presents the NO_x emission results for the NEDC tests, both cold and hot. In the cold cycles, the results were above the Euro 6 limit, with higher values observed at the case of the realistic road load. On the other hand, in the hot cycles NO_x emissions were below the limit and this is attributed probably to the more efficient operation of the SCR system at higher temperatures.

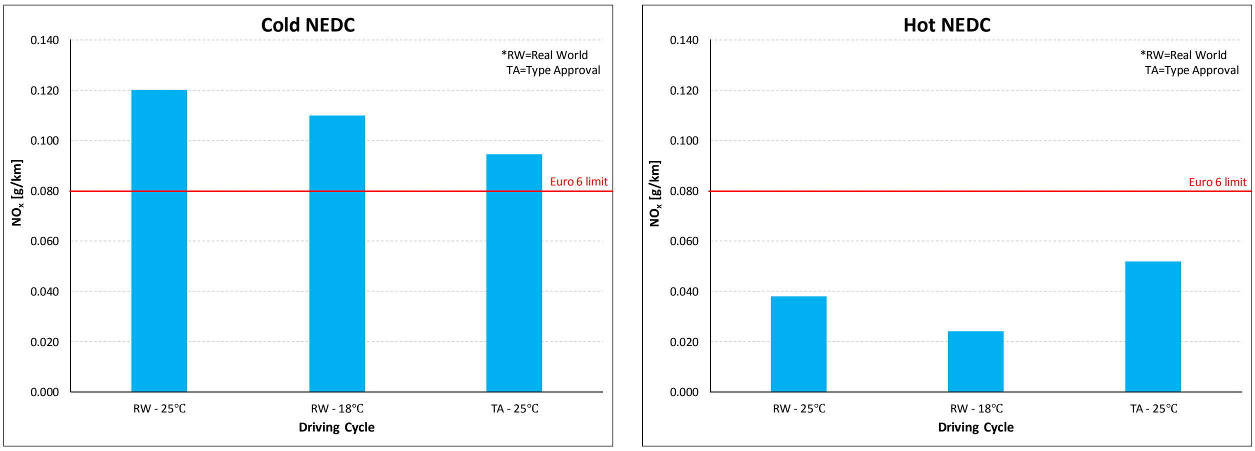


Figure 26: NO_x emissions in cold NEDC (left) and hot NEDC (right)

3.4 Vehicle 4: VW Polo 1.2 TSI

The VW Polo was the fourth vehicle tested in the context of this study, the only one equipped with a turbocharged gasoline direct injection (GDI) engine. The main technical specifications of this vehicle are presented in Table 36. As usually in gasoline engines, the vehicle is not equipped with a Mass Air Flow (MAF) sensor, but the calculation of the intake air flow is based on the signal of a Manifold Absolute Pressure (MAP) sensor. Therefore, the available OBD signals do not provide any values for the intake air flow. In order to overcome this, an external MAF sensor was fitted in the intake manifold, as shown in Figure 27, with its signal being recorded in an external data recording unit. Table 37 summarizes the valid on-road tests conducted for this vehicle. In total, three RDE-compliant and two dynamic tests were conducted. Table 38 presents the ambient temperature during the on-road tests.

Table 36: VW Polo technical specifications

MY & Chassis type	2015, Hatchback
Engine	Gasoline, 4-cyl
Drive & Transmission	FWD, Automatic
Number of gears	7
Max power [kW]	66
Engine capacity [cm^3]	1197
Start-stop	Yes
Euro class	6
Aftertreatment system	TWC
Type approval CO_2 [g/km]	109
Mileage (start of testing) [km]	5,930

Figure 27: Extra MAF sensor

Table 37: VW Polo 1.2 TSI test schedule.

Type of test	Number of tests
Standard RDE	3
Standard DYN	2

Table 38: Ambient temperature during on-road testing

	VW Polo 1.2TSI				
	RDE1	RDE2	RDE3	DYN1	DYN2
min	20.2	18.8	21.2	23.9	23.8
max	25.9	23.7	25.5	30.8	26.0
average	23.7	20.6	23.1	27.0	24.8

Table 39 summarizes the emissions for all the tests. Beginning with CO_2 emissions, RDE3 presents somehow higher total values than the other two RDE-compliant tests, with the deviation being observed in all three parts of the route, as shown in

Table 40. On the other hand, the dynamic tests exhibit significantly higher CO_2 emissions (and fuel consumption, correspondingly), owing to the higher engine speed and loads experienced during this route.

Concerning NO_x and CO emissions, very low values are observed in the case of all the RDE-compliant tests, well below the respective Euro 6 limits (60mg/km and 1g/km for NO_x and CO emissions, respectively). Especially for NO_x emissions, these remain below the limit in all the three parts of the RDE-compliant tests, as shown in Table 41. Apparently, the operation of the TWC at the hot-started, i.e. above the light-off temperature, RDE-compliant route results in very low NO_x and CO emissions. On the other hand, both NO_x and CO emissions exhibit increased values in the dynamic tests (Table 39 and Table 41), significantly higher than the respective limit, due to the higher engine speed and loads experienced during this route. Although that DYN tests are also hot-started, the abrupt accelerations and the uphill driving cause engine operation at high loads and fuel enrichment operation, resulting ultimately in increased pollutant emissions. Finally, Table 42 presents the average emissions of the three parts of the RDE-compliant tests, the average total emissions of the RDE-compliant tests and the total emissions of the DYN test.

Table 39: Total trip emissions for all repetitions

All emissions, MAW method except DYN1 & DYN2					
	RDE 1	RDE 2	RDE 3	DYN 1	DYN 2
CO_2 [g/km]	117.2	114.9	127.2	171.2	165.8
NO_x [mg/km]	10.4	8.5	15.6	170.8	125.9
CO [mg/km]	21.3	13.5	16.3	3063.2	1680.8
NO [mg/km]	9.9	8.1	15.4	167.9	125.3
NO_2 [mg/km]	0.5	0.4	0.2	2.9	0.6

Table 40: CO_2 emissions of the total trip and the urban, rural, motorway parts

CO_2 [g/km], MAW method except DYN1 & DYN2					
	RDE 1	RDE 2	RDE 3	DYN 1	DYN 2
Urban	131.5	127.5	145.8		
Rural	95.8	94.5	104.1		
Motorway	123.9	122.3	131.2		
Total	117.2	114.9	127.2	171.2	165.8

Table 41: NO_x emissions of the total trip and the urban, rural, motorway parts

NO_x [mg/km], MAW method except DYN1 & DYN2					
	RDE 1	RDE 2	RDE 3	DYN 1	DYN 2
Urban	17.1	17.1	23.1		
Rural	8.7	5.5	6.9		
Motorway	5.2	2.6	16.7		
Total	10.4	8.5	15.6	170.8	125.9

Table 42: Average emissions of RDE trips and DYN trips

Average of RDE1-RDE3 and DYN1-DYN2					
	CO_2 [g/km]	NO_x [mg/km]	CO [mg/km]	NO [mg/km]	NO_2 [mg/km]
RDE Urban	134.9	19.1	1.0	18.3	0.8
RDE Rural	98.1	7.0	5.9	6.8	0.2
RDE Motorway	125.8	8.2	44.6	8.0	0.2
RDE Total	119.8	11.5	17.0	11.1	0.4
DYN Total	168.5	148.3	2372.0	146.6	1.7

The following figures (Figure 28 – Figure 31) illustrate the instantaneous CO_2, CO and NO_x mass flows during the RDE1 test and DYN1 tests. Under regular driving (RDE-compliant route), CO and NO_x emissions are very low Figure 29). The much more dynamic driving style and profile of the DYN 1 test causes higher average emissions (CO_2, CO and NO_x) than regular driving and much higher peak emission values (Figure 30 and Figure 31).

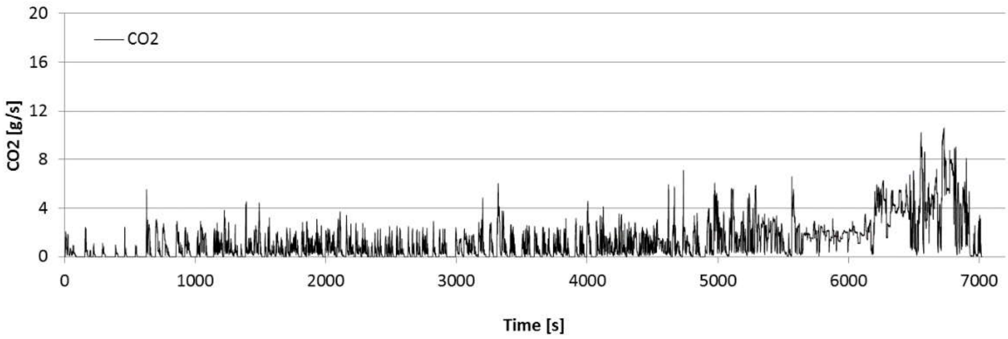


Figure 28: Instantaneous CO_2 emission mass flow during the RDE 1 test.

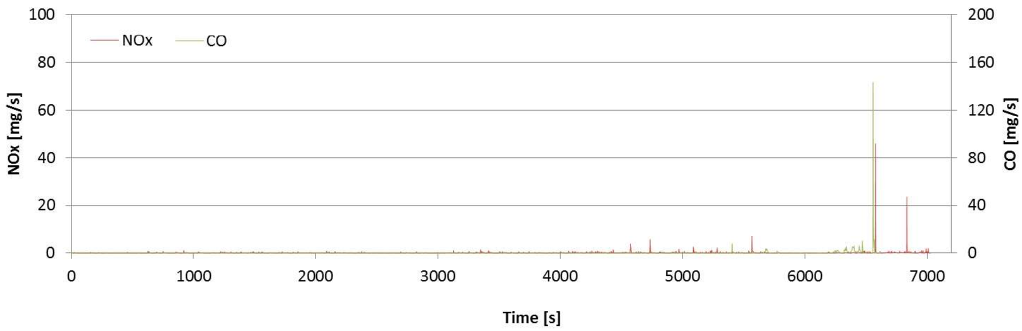


Figure 29: Instantaneous CO and NO_x emissions mass flow during the RDE 1 test.

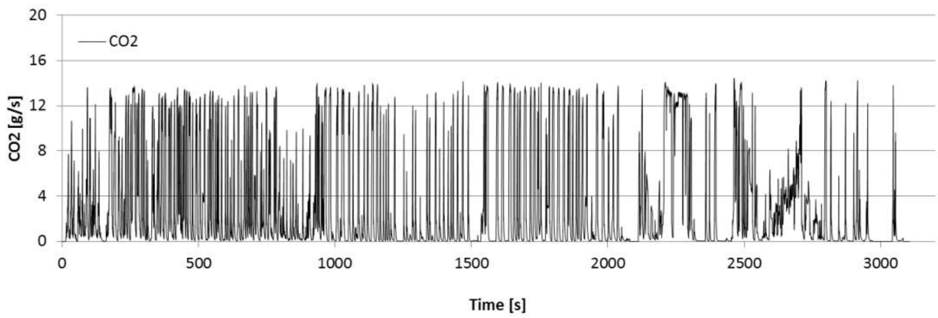


Figure 30: Instantaneous CO_2 emission mass flow during the DYN 1 test.

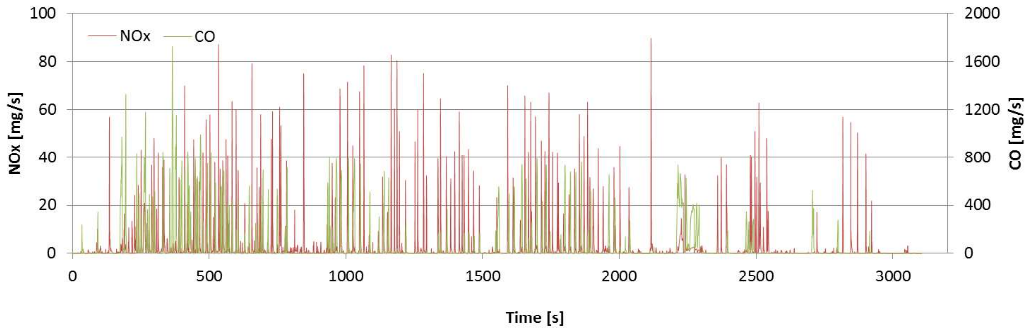


Figure 31: Instantaneous CO and NO_x emissions mass flow during the DYN 1 test.

The on-road test results of the VW Polo 1.2 TSI concluded to 120±7 gCO_2/km following a regular RDE-compliant driving profile and 168±3 gCO_2/km following a dynamic driving profile. Also, following the RDE-compliant route, the average NO_x exceedance factor (EF) was 0.2 for the total trip and 0.32 for the urban part. The respective EF for NO_x in the dynamic route was 2.5±0.4, as also shown in Table 43. It is also interesting to note that in the dynamic route, CO emissions presented high values, with the EF being 2.3±0.7 (Table 43), while in the RDE-compliant route the respective EF value is practically 0. Apparently, the operation of the TWC at the hot-started, i.e. above the light-off temperature, RDE-compliant route results in very low NO_x and CO emissions. Finally, as regards vehicle driving dynamics, the RDE-compliant trips were found within the legislation limits, while the dynamic ones where significantly above the limit. Specifically, Figure 32 presents the average v*a parameter for urban, rural and motorway parts of the RDE-compliant and DYN trips.

Table 43: Average exceedance factors for the measured tests

EF	NO_x	CO
RDE Urban	0.32	—
RDE Total	0.20	—
DYN Total	2.5 ± 0.4	2.3 ± 0.7

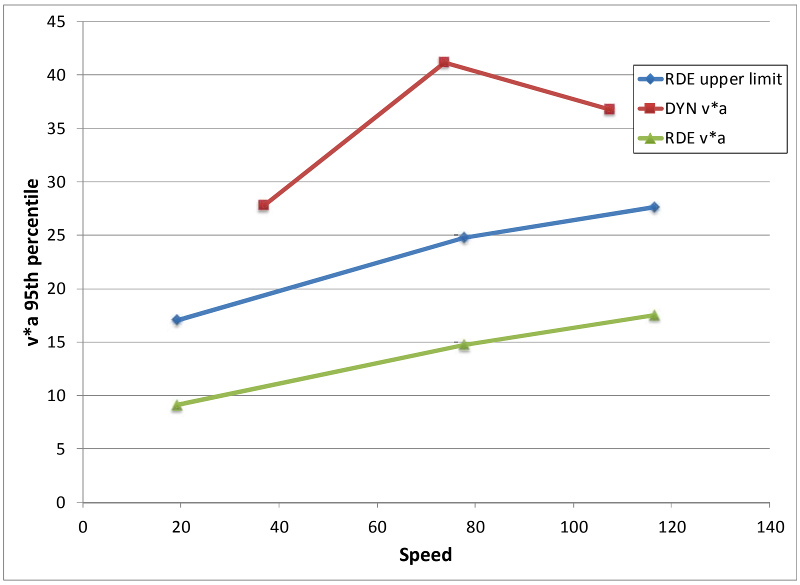


Figure 32: Average v*a 95th percentile for the RDE-compliant and the dynamic trips

3.4.1 Coast-down and Laboratory Testing

Before running the laboratory tests, a coast-down was conducted in order to determine the realistic road load of the vehicle, to be used on chassis dyno measurements. Table 44 presents the realistic coast-down time together with two values for NEDC. By the time of testing on the chassis dyno, the actual NEDC TA road load was not available, therefore the vehicle was tested using the road load (NEDC tested) from a similar vehicle – another VW Polo with similar characteristics. At a later stage, the correct NEDC TA road load was made available and an analysis was conducted in order to assess the effect on CO_2 emissions. This analysis is presented at the end of this paragraph. As shown in Table 44, the total realistic deceleration time is lower than the NEDC TA one by 28 sec and by 46 sec compared to the NEDC tested one.

Table 44: Coast-down times

Conditions	Coast-down time [s]
NEDC tested	210
NEDC TA	192
Realistic	164

During the chassis dyno measurements, Start-stop was not operational, although that not any errors were found in the ECU. Table 45 summarizes the emission and fuel consumption results of the chassis dyno measurements. All tests were conducted at 25ºC, as the typical temperature for NEDC testing, and were repeated at a lower temperature, around 18ºC. NEDC was tested with both realistic and type approval road load, the latter just to confirm the normal operation of the vehicle.

Figure 33 presents the CO_2 emission results for the NEDC tests, both cold and hot. The road load effects are prominent in these measurements. In the cold NEDC, the difference in CO_2 emissions was 7 g/km when comparing the case with realistic road load with the type approval road load one. At the hot cycle, the respective difference was 6.3 g/km. In WLTC, the lower test temperature caused an increase in CO_2 emissions in the order of 3.6 and 3 g/km in the cold and hot start cycles, respectively.

Figure 34 presents the NO_x emission results for the NEDC tests, both cold and hot. In all cases, the values are below the Euro 6 limit. (0.060 g/km). At the case of hot cycles, NO_x emissions are lower than the respective in cold cycles, owing to the more efficient operation of the TWC. It is interesting to note that the cold-started NEDC at 25^{0}C presents the lowest CO_2 emissions but not the lowest NO_x ones.

Table 45: Chassis dyno results for the VW Polo

Driving Cycle	Start	Road Load	Temperature (°C)	CO_2 [g/km]	CO [g/km]	HC [g/km]	NO_x [g/km]	NO [g/km]	FC [l/100 km]	PM [mg/km]	PN [#/km]
NEDC	Cold	Real World	25	133.0	0.158	0.017	0.013	0.009	5.60	0.34	—
	Cold	Real World	19	130.4	0.354	0.159	0.041	0.025	5.52	0.39	—
	Cold	Type Approval	25	126.0	0.170	0.015	0.016	0.011	5.31	—	4.55E+11
	Hot	Real World	25	125.1	0.022	0.001	0.009	0.006	5.26	0.15	—
	Hot	Real World	19	125.2	0.023	0.002	0.006	0.005	5.26	0.35	2.84E+11
	Hot	Type Approval	25	118.8	0.030	0.003	0.010	0.008	4.99	—	1.76E+11
WLTC	Cold	Real World	25	127.1	0.169	0.012	0.011	0.007	5.35	—	6.28E+11
	Cold	Real World	20	130.7	0.215	0.017	0.014	0.009	5.51	—	7.53E+11
	Hot	Real World	25	125.1	0.027	0.002	0.013	0.009	5.26	—	3.41E+11
	Hot	Real World	23	128.1	0.019	0.002	0.013	0.010	5.38	—	3.27E+11
Artemis	Urban (cold)	Real World	25	216.3	0.840	0.000	0.014	0.012	9.14	0.889	—
	Urban (hot)	Real World	25	211.1	0.000	0.000	0.033	0.022	8.87	0.781	—
	Road	Real World	25	106.2	0.008	0.000	0.012	0.008	4.46	0.201	—
	Road	Real World	19	106.9	0.007	0.002	0.011	0.007	4.49	0.25	3.44E+11
	Urban (hot)	Real World	23	213.4	0.014	0.004	0.042	0.029	8.97	—	4.00E+11

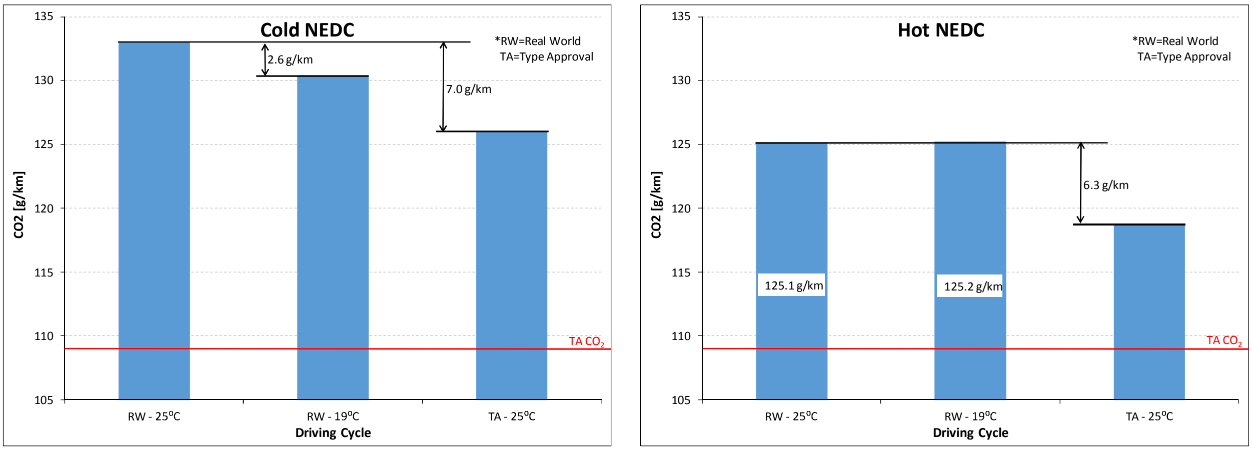


Figure 33: CO_2 emissions in cold NEDC (left) and hot NEDC (right)

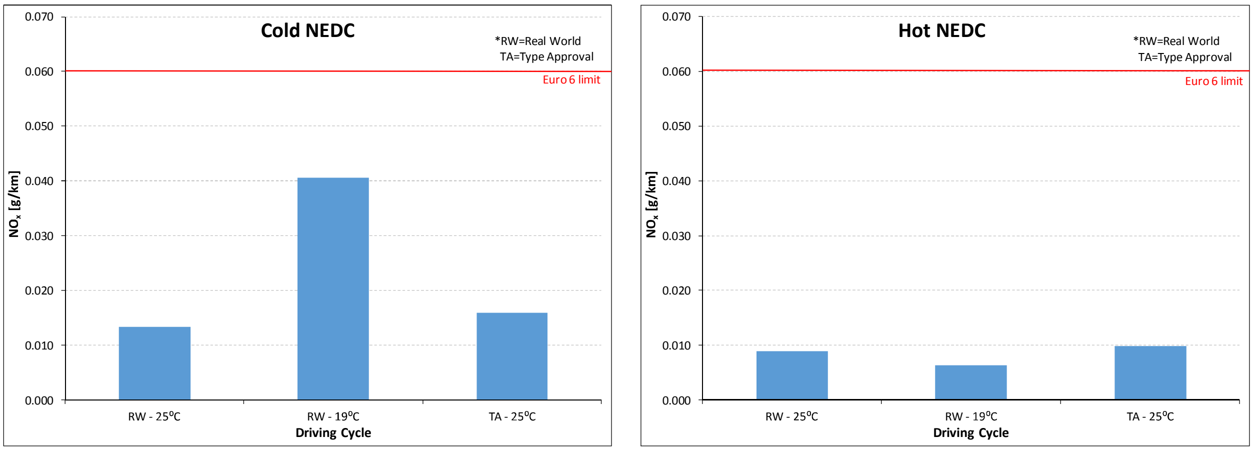


Figure 34: NO_x emissions in cold NEDC (left) and hot NEDC (right)

As already mentioned, by the time of testing on the chassis dyno, the actual NEDC TA road load was not available, therefore the vehicle was tested using the road load (NEDC tested) from a similar vehicle – another VW Polo with similar characteristics. After the correct NEDC TA road load has been made available, the following analysis was conducted in order to assess the effect on CO_2 emissions.

The analysis was conducted on a simulation basis and its target was to evaluate the impact of the different road load on fuel consumption and CO_2 emissions during the cold and hot NEDC. To this aim, an existing simulation model (developed in the past by LAT in Cruise) for the VW Polo was implemented. Figure 35 presents the layout of the model.

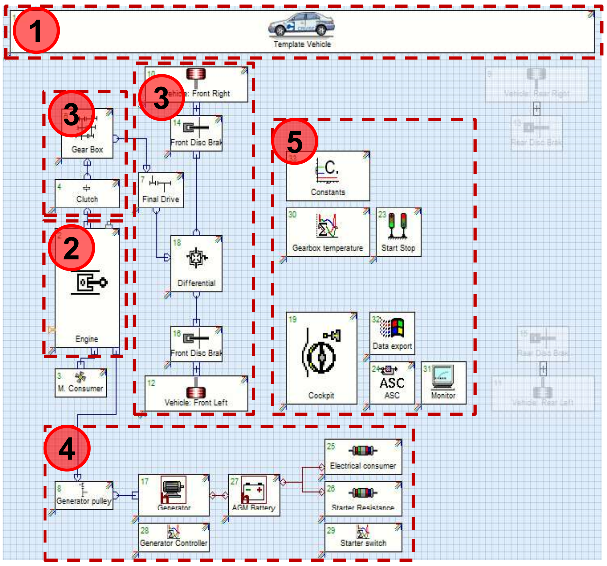


Figure 35: Layout of the simulation model in Cruise

The main components of the model are:

- Vehicle: Road load & vehicle mass
- Internal combustion engine: FC map, full load & motoring curve, engine specs.
- Drivetrain: Gearbox & final drive ratios & efficiency, wheels
- Electrical system: Battery, generator, el. consumptions
- Controllers: Driver, start & stop

Since the only target of this approach is the evaluation of the road load effect, all the other parameters remained constant between the two cases. Figure 36 shows the two road loads and their difference, where it is observed that the main difference is in the low speed range.

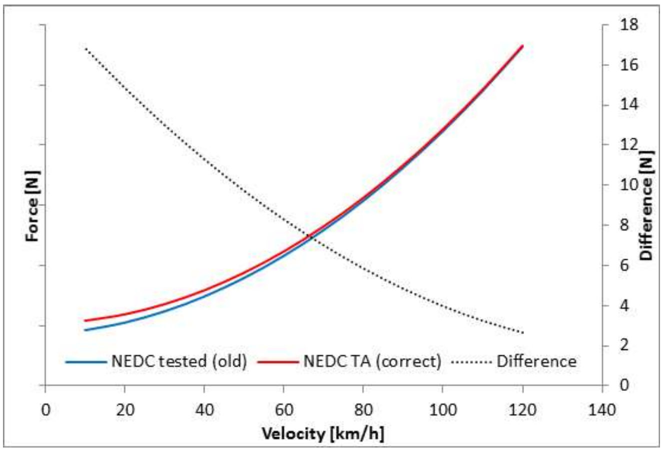


Figure 36: The tested and the TA NEDC road load

Using the model, fuel consumption and CO_2 emissions for NEDC are calculated for the tested and the actual (TA) Road Load. The results presented in Figure 37 indicate that with the actual RL, CO_2 emissions are higher by 1.1 g/km for cold and 1.3 g/km for hot NEDC. As a result, if the vehicle had been tested with the actual RL, CO_2 emissions were expected to be approximately 1 g/km higher. With the same approach, fuel consumption was expected to be approximately 1% higher. From the results, the highest difference is detected in the Urban part (UDC), resulting directly from the difference of the two road loads in the low speed range (Figure 36).

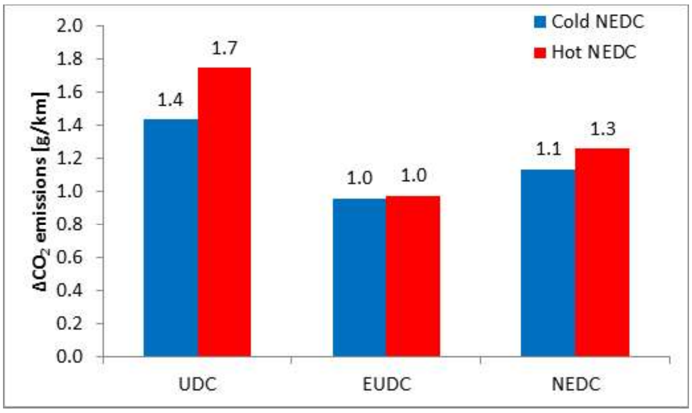


Figure 37: CO_2 emission difference for the different road loads

The difference between the two RLs is higher for velocity lower than 70 km/h. In Figure 38 the instantaneous fuel consumption during NEDC is compared for the two road loads, where a slight difference during the constant velocity periods can be observed.

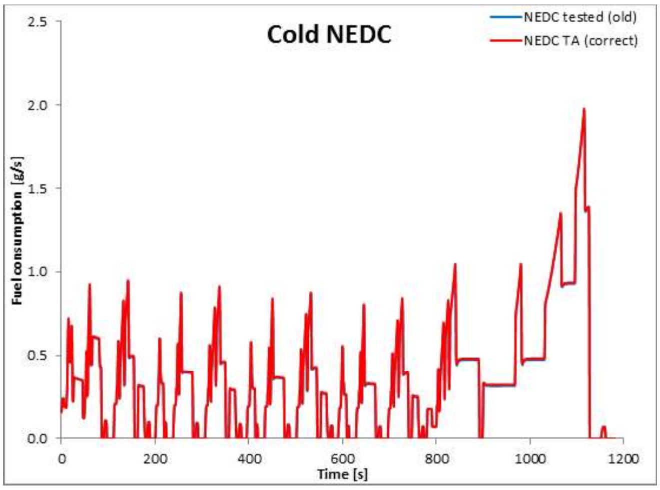


Figure 38: Instantaneous fuel consumption during NEDC with the two road loads

4 Summary and Future Steps

This report summarized the work conducted by EMISIA SA and LAT in the context of a testing campaign and experimental study funded by the International Council on Clean Transportation (ICCT). The work was related to the emissions testing on four vehicles of different technology, all of which Euro 6 compliant, and under various driving conditions, both in laboratory and on-road using a Portable Emissions Measuring System (PEMS).

Four vehicles were tested, three diesels and one gasoline, all of them sourced by rental companies, meaning that they were used vehicles. Two diesel vehicles were equipped with LNT and the third with SCR, while the gasoline vehicle was powered by a turbocharged direct injection engine and was equipped with a TWC. All vehicles were tested in the same RDE-compliant route, while an additional dynamic trip was also followed. The testing campaign assisted the assessment of the real-world behavior of the tested vehicles and of different technologies. Further, all the vehicles were tested in the laboratory, under NEDC, WLTC and Artemis cycles, using the realistic road load. The latter was determined by a coast-down test conducted on a suitable track. A NEDC measurement with the TA road load was also included at the end of testing.

According to the findings of this experimental campaign, the following can be concluded (illustrated also in Figure 39):

- The NO_x emission control devices for diesel engines are not capable of keeping NO_x emissions during real-world driving within the required limits. The three diesel vehicles tested in this study presented significantly higher NO_x emissions during on-road testing, exceeding the limit of the temporary conformity factor (CF) of 2.1.
- When the diesel vehicles were driven in RDE-compliant routes, then they exceeded the Euro 6 NO_x emissions limit (80 mg/km) by 5 to 16 times, which is much higher than the temporary CF. The extreme values were observed for the two LNT-equipped vehicles, while an intermediate value was observed for the SCR-equipped vehicle. A number of other parameters also affect the final observation, e.g. the EGR strategy followed by each vehicle.
- When driven in a more dynamic route, then the respective exceedance factor (EF) was from 26 to 40.
- In the case of the gasoline vehicle, NO_x emissions remained well below the Euro 6 limit during the RDE-compliant route, highlighting the effectiveness of the TWC. However, this was not the case under more dynamic driving, where both NO_x and CO emissions presented high values.

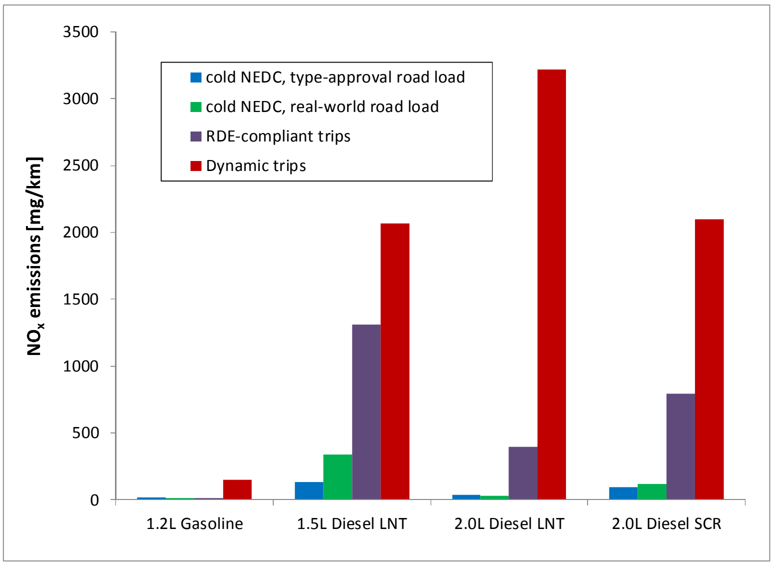


Figure 39: NO_x emissions under laboratory and on-road tests

The activities in the context of this study provide a good basis for further testing and investigation on real-world emissions. It is interesting to expand the investigation in other vehicles with different engine technologies, such as a GDI lean-burn vehicle or a GDI vehicle equipped with GPF, focusing on NO_x and PN emissions, as well as on CO_2 emissions and fuel consumption. It is important also to include engine cold start in the RDE tests and run additional dynamic routes in order to evaluate the effects of different driving styles.