Portable Nano-Particle Emission Measurement System

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Publishable Executive Summary

The PEMs4Nano project addresses the development of both a new portable device and a laboratory system to detect particles down to sizes as small as 10 nm together with a robust procedure to measure these particles. Achieving robust and reliable measurement technology and procedures supports the automotive industry in reducing vehicle emissions providing a contribution to future regulation on particle emissions as well as a better understanding of particle emissions below 23 nm (with the threshold of at least 10 nm).

IDIADA, as a WP 4 leader, will perform a final validation using the new technology developed in WP 2 through physical testing in laboratory and on real road with the final objective of ensuring the correct operation of the new PN measurement systems to measure small particles down to 10 nm.

The aim of this section is the definition of the procedures to be followed during the testing campaign: selection of the test vehicle, testing procedures, the suggested instrumentation and the most suitable equipment to be used, defining how and where to perform the measurements.

The procedure to select the two test vehicles takes into account that these vehicles should cover different range of PN emissions, so should be considered different emission regulations, sizes of engine, PN after-treatment and segments, and also should be in top positions in the top-selling list.

The testing procedures are based on the standard protocols for WLTP, US06 and Artemis 130 (on the chassis dynamometer) and RDE tests (on real road) but with some adaptations to the PEMs4Nano project needs, such as the addition of second-by-second diluted and raw exhaust emissions measurements of standard gases and the measurement of particle number particle size over 10 nm and 23 nm independently.
The WLTP cycle is selected because it was developed using real-driving data, gathered from around the world. WLTP therefore represents better every day driving profiles than NEDC test, which is based on a theoretical driving profile. The US06 Supplemental Federal Test Procedure in combination with Artemis 130 is selected as a representation of aggressive, high-speed and high acceleration driving behaviour and rapid speed fluctuations. RDE complements WLTP laboratory test ensuring that cars deliver low emissions over on-road conditions.

Finally, after the definition of the test vehicles, test cycles and testing procedures above, a test matrix is defined taking into account different configurations of PN measurement.

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1 Introduction

The PEMs4Nano project addresses the development of both a new portable device and a laboratory system to detect particles down to sizes as small as 10 nm together with a robust procedure to measure these particles. Achieving robust and reliable measurements technology and procedures supports the automotive industry in reducing vehicle emissions providing a contribution to future regulation on particle emissions as well as a better understanding of particle emissions below 23 nm (with the threshold of at least 10 nm).

IDIADA, as a WP 4 leader, will perform a final validation using the new technology developed in WP 2 through physical testing in laboratory and on real road with the final objective of ensuring the correct operation of the new PN measurement systems to measure small particles down to 10 nm.

The aim of this section is the definition of:

- vehicle characteristics
- vehicle preparation and instrumentation
- testing procedures to be performed on the vehicles (including equipment checking, facilities set-up)
- measurement considerations including a test matrix defining how and where to perform the measurements

These testing procedures will be based on the standard protocols for WLTP, US06 and Artemis 130 (on the chassis dynamometer) and RDE tests (on real road) but with some adaptations to the PEMs4Nano project needs (including additional instrumentation and some additional measurements). The WLTP cycle is selected because it was developed using real-driving data, gathered from around the world. WLTP therefore represents better every day driving profiles than NEDC test, which is based on a theoretical driving profile. The combination of the US06 Supplemental Federal Test Procedure and Artemis 130 is selected as a representation of aggressive, high-speed and/or high acceleration driving behaviour, rapid speed fluctuations, and driving behaviour following start-up. RDE complements WLTP laboratory test ensuring that cars deliver low emissions over on-road conditions.

2 Vehicle definition

The selection of the vehicles to be tested in WP4 will be performed taking into account that the new lab PN10nm and PEMS PN10nm measurement systems need to be suitable to measure PN of Gasoline Direct Injection (GDI) vehicles with different features:

- From Euro 5 to Euro 6d Temp emissions Regulation
- Different sizes of engines (1.0, 1.4, 2.0 L)
- With different PN after-treatment (with or without GPF)
- Different vehicle segments (B/C-segment, SUV-segment)

The two vehicles selected (Vehicle 1 and Vehicle 2) should cover these above characteristics and should be also in the top positions in the top-selling list.

More specifically, the two vehicles should fulfil the following requirements:

<u>Vehicle 1 (expected low PN emission vehicle):</u>

- 2018 top-Selling Vehicle
- B/C-segment
- Euro 6d-Temp Emission Regulation
- 1.0-1.4L GDI engine with GPF
- Examples: VW Golf, Ford Focus, Ford Fiesta, Peugeot 208, Citroen C3, etc.

<u>Vehicle 2 (high PN emission vehicle):</u>

- 2017 top-Selling Vehicle
- SUV-segment
- Euro 5-6c Emission Regulation
- 1.4-2.0 L GDI engine without GPF
- Examples: Nissan Qashqai, Volkswagen Tiguan, Hyundai Tucson, etc.

Additionally, to obtain some repetitive tests, the mileages of these vehicles should be higher than 3000 km.

3 Vehicle preparation

Before starting the testing activities, some tests will be performed on the vehicle in order to check if the overall vehicle is in proper conditions to start the measurement campaign. These preparations are as follows:

- Identification of the vehicle
- Vehicle body clean-up
- Visual inspection to detect any external damage
- Safety static and dynamic check
- Fill the fuel tank
- Instrumentation of the vehicle
- Inflate the tyres to the test specifications

4 Test Cycles Definition

This section defines the different test cycles to be performed with both the new laboratory system (lab PN10nm) and the on-board system (PEMS PN10nm).

During the testing campaign, four test cycles will be performed both on chassis dynamometer and on real road. The objective of doing different cycles is to obtain as many results as possible with the new systems in different conditions (vehicle speed, forces, etc.) in order to check the correct operation of the new PN systems.

The WLTC cycle and the US06 together with the Artemis 130 cycle (Hot Test) will be performed on chassis dynamometer. The first one will be used as a reference due to the fact it is the cycle established by the new legislation, replacing the old NEDC. The combination of the other two cycles is meant to give us very reliable information on how the new equipment systems work with a high vehicle speed and high load values, which will have a greater number of particles. The RDE tests on real road will be performed in order to evaluate the new on board system in real driving conditions.

Additionally, some tests will be performed with both new lab PN10nm as well as the PEMS PN10nm in order to compare and correlate the results.

4.1 WLTC Tests

The WTLC testing procedures on Chassis Dynamometer will be based on the standard WLTC procedure but with some adaptation to the PEMs4Nano project needs. Exhaust emission tests at ambient temperature according to the specifications of Commission Regulation (EU) 2018/1832 will be performed.

The cell temperature for all tests will be 23ºC +/- 3ºC. The exhaust emissions from the vehicles will be measured using a chassis dynamometer and a conventional constant volume sampling (CVS) system with a critical flow venture. The roller bench of the chassis dynamometer will be a 2WD roller type. To follow the legislative cycle, the driver will be assisted by a driver aid system.

The WLTC is composed of four speed phases (low, medium, high and extra-high) and lasts 1800 s, features a more dynamic speed profile and a higher mileage than NEDC.

The WLTC test procedure will be as follows:

1. E10 Euro 6 reference fuel addition if it is necessary.
2. Nominal tires pressure check, as indicated by the manufacturer.
3. Run the preconditioning cycle (WLTC) at 23ºC +/- 3ºC.
4. Vehicle soaking at ambient temperature in the soak room at a constant temperature of 23ºC with a tolerance of ±3ºC (minimum 6 hours maximum 36 hours).
5. Perform a Type I WLTC emission test.

The corresponding WLTC test cycle is shown in Image 1 below:

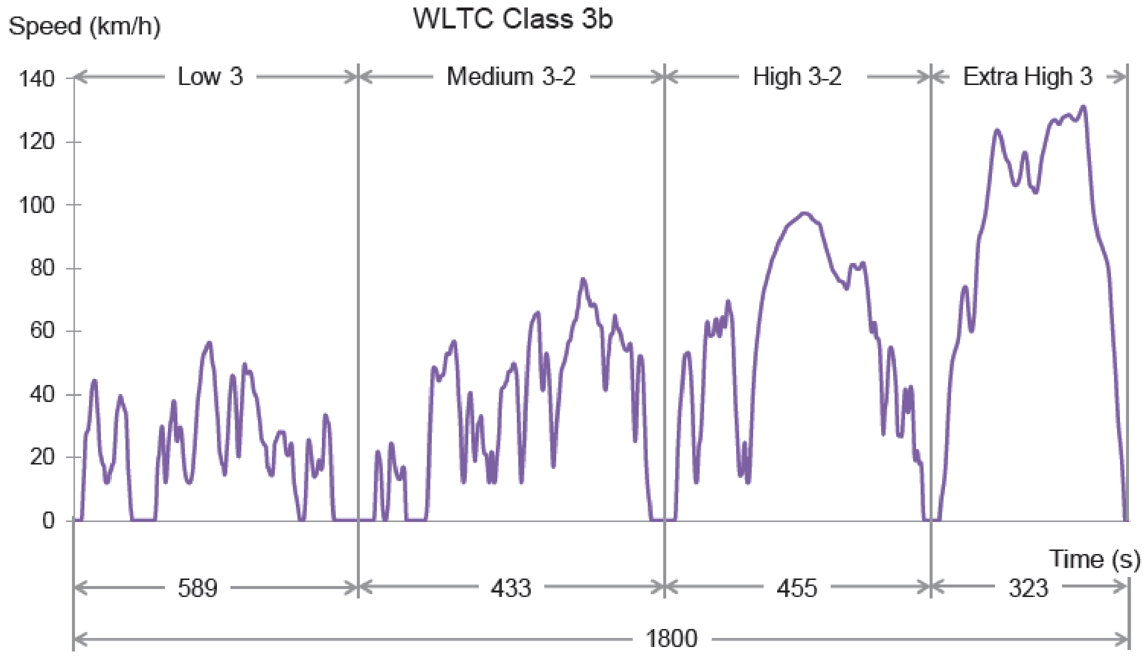

Image 1. WLTC test cycle

The emissions measurement of these tests will be performed according to configurations A and B detailed in section 6.1 and 6.2.

4.2 US06 + Artemis 130 Tests

As mentioned above, the 2nd Test to be performed on Chassis Dynamometer is composed of the EPA standard cycle US06 in cold conditions and the Artemis 130 Cycle just after finishing the first US06 cycle (hot conditions).

The cell temperature for all tests will be 23ºC +/- 3ºC. The exhaust emissions from the vehicles will be measured using a chassis dynamometer detailed in section 4.1.

The test procedure of each US06 + Artemis 130 emission test will be as follows:

1. Vehicle soaking at ambient temperature in the soak room at a constant temperature 23ºC with a tolerance of ±3ºC (minimum 6 hours maximum 36 hours).
2. E10 Euro 6 reference fuel addition if it is necessary.
3. Nominal tires pressure set, as indicated by the manufacturer.
4. Run a warm-up preconditioning US06 cycle at 23ºC +/- 3ºC just before the step 5.
5. Perform US06 emission test.
6. Perform Artemis 130 emission test.

The corresponding US06 and Artemis 130 cycle is shown in Image 2 and Image 3 below:

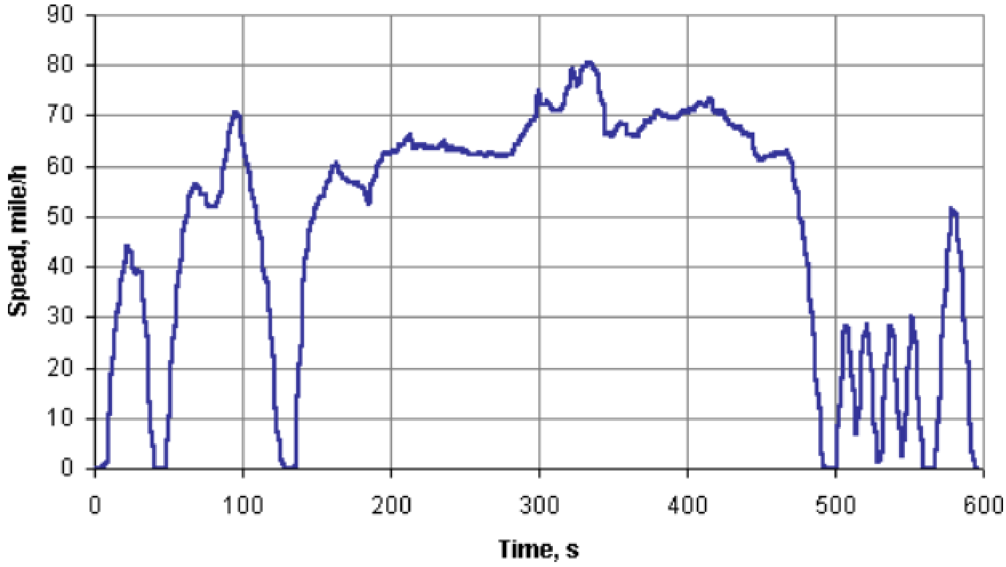

Image 2. US06 test cycle

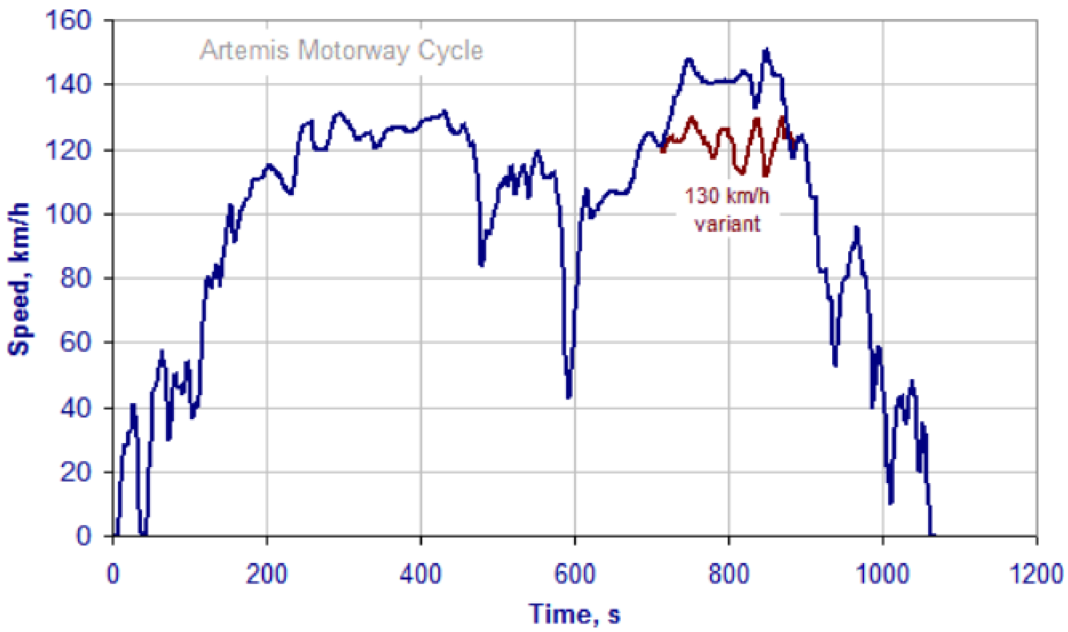

Image 3. Artemis 130 test cycle

The emissions measurement of these tests will be performed according to configurations A and B detailed in sections 6.1 and 6.2.

4.3 RDE Tests

The RDE testing will be based on the standard procedure included in COMMISSION REGULATION (EU) 2018/1832 of 5 November 2018.

The RDE test procedure to determine the emissions will be as follows:

1. Installation of the PEMS equipment components on the vehicle. Exhaust flow meters will be attached to the tailpipe and a GPS and a weather station will be installed in the external area of the vehicle. The instrumentation is detailed in the following Table 4-1:

Table 4-1. RDE Equipment instrumentation

EQUIPMENT
PEMS
Gas Analyser Module: determination of CO, CO2, NOx and NO
PN module to measure PN 23 nm
Pitot Flowmeter
GPS to determine the position, altitude and speed of the vehicle
Weather station to measure environmental conditions
Data Acquisition System
Data Logger
Power Supply
Lead-acid Battery
GAS BOTTLES
Span and air calibration gas

2. Refilling of the vehicle's fuel tank with E10 Euro 6 reference fuel.
3. Tyre pressure set, as indicated by the manufacturer for the vehicle weight.
4. Vehicle soaking at ambient temperature in the soak room at a constant temperature of 23ºC with a tolerance of ±3ºC (minimum 6 hours maximum 36 hours).
5. Vehicle battery charging during soak period.
6. External batteries for PEMS equipment charging during soak period.
7. Pre-test procedures to ensure correct operation of the PEMS equipment, the additional instrumentation and scan tool for ECU data.
8. Performance of the RDE trip under moderate temperature and altitude conditions.
9. Post-test procedures including the drift check of the analysers.

The emissions measurement of these tests will be performed according configuration C detailed in section 6.3.

The route selected by IDIADA has the following characteristics:

- Theoretical duration: 5700 s
- Trip distance: 85,4 km
- Theoretical distance of each part
    - Urban distance: 26 km
    - Rural distance: 27 km
    - Motorway distance: 32,4 km
- Theoretical shares:
    - Urban share: 30,4 %
    - Rural share: 31,6 %
    - Motorway share: 38,0 %
- Start and end elevation absolute difference: 56 m
- Altitude minimum - maximum: 45 m - 435 m
- Theoretical urban stop time: 11 %

A representative speed of the route is shown in the following Image 4 with separation of the three parts, so that the trip shall consist of an Urban Part (speeds up to 60 km/h), a Rural Part (vehicle speeds between 60 km/h and 90 km/h) and a Motorway Part (speeds above 90 km/h).

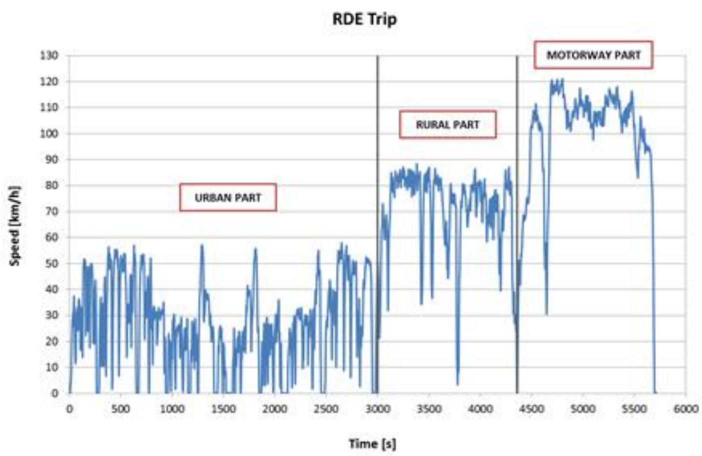

Image 4. Speed profile of RDE Trip

A representative altitude profile of the route is shown in the following Image 5:

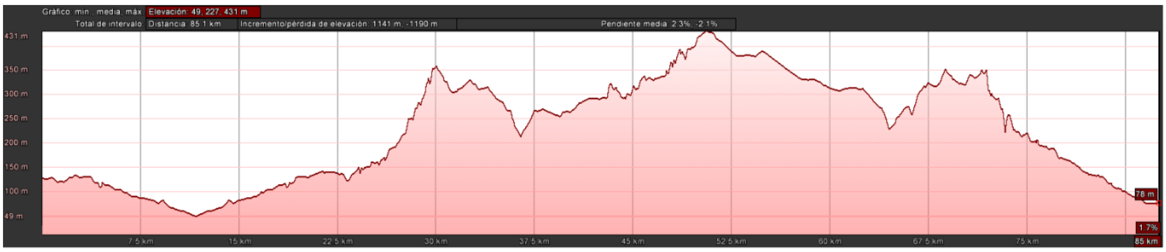

Image 5. Altitude profile of RDE Trip

5 Equipment checking and facilities set-up

In this part of the deliverable, the check and set-up in IDIADA's facilities of both the laboratory and the on-board system will be described. This action is done at IDIADA facilities with the collaboration of Horiba.

5.1 PEMS PN10nm system

The PEMS PN10nm developed by the PEMs4Nano partners will be used for measuring the particle number with a threshold of 10 nm. This equipment will be used together with the actual PEMS PN23nm (system currently used in RDE testing for homologation). Following considerations have to be taken into account:

- ***Trigger functionality:*** A trigger will be used to make sure both systems start at the same time.
- ***Y-Split functionality:*** It was decided to measure both PEMS PN10nm and PEMS PN23nm at the same sample point with a Y-Split provided by Horiba. In order to ensure there is no influence caused by splitting the air flow in two, some preliminary tests changing the position of the sample lines were performed.

In addition, in order to ensure the good functionality of the equipment, some preliminary checks were performed:

- ***PN Zero (PN Functionality Check):*** With a HEPA filter, this action consists of ensuring that the concentration measured with the filter is close to 0#/cm^3. Hence, there is no background concentration.
- ***Air flow coming from the exhaust hot line:*** The air flow at the end of the sample hot line must be around 0.7 L/min (standard conditions). A TSI flow meter was used to measure the air flow.

Finally, once the checking of the equipment had been done, the PEMS PN10nm system was set-up in the test cell by performing a preliminary test to see the behaviour of the particles measured by the on-board system. In order to have an idea, the approximately timeframe of the procedure that needs to be performed for each test on the PEMS PN10nm system is the following:

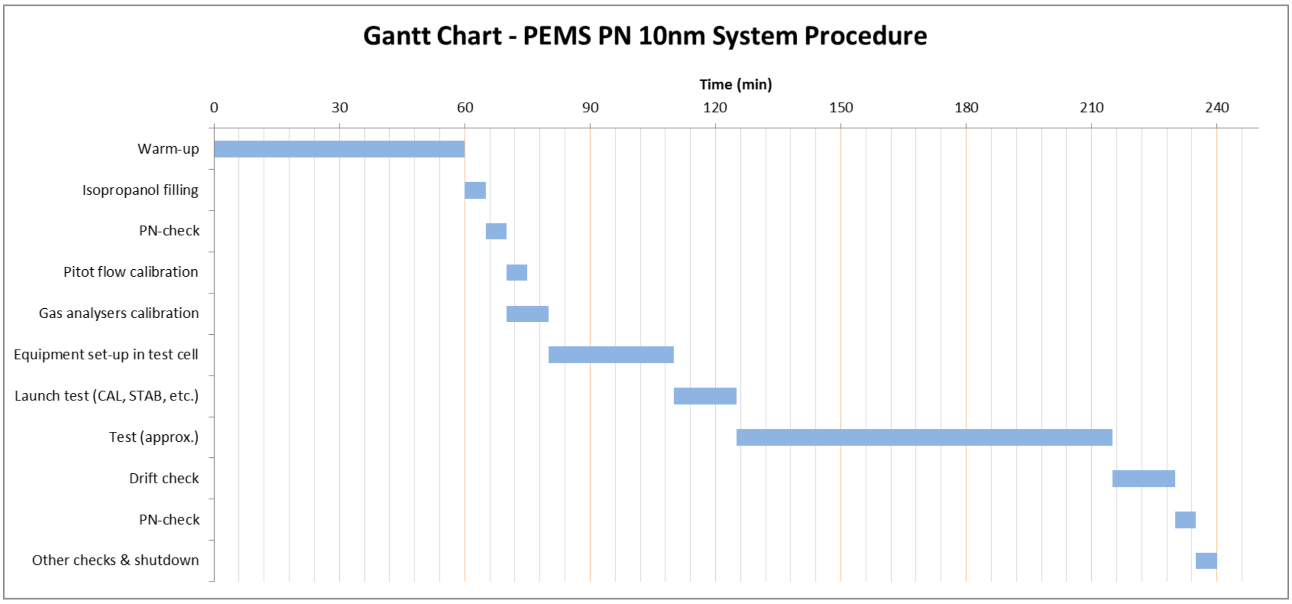

Image 6. Gantt Chart – PEMS PN 10nm System Procedure

5.2 Lab PN10nm system

The new lab PN10nm capable of measuring particles below 23 nm to at least 10 nm will also be used at IDIADA during the testing campaign in order to perform a final validation of the equipment and a robustness evaluation by performing the different tests already defined in this deliverable.

In order to ensure good behaviour of the new lab PN10nm system, some preliminary checks were done at IDIADA facilities by performing a pre-test in the test cell. In that test, the equipment was checked according to the procedure explained in deliverable *D4.1 – Implementation of the calibration procedure.*

In order to have an idea, the approximately timeframe of the procedure that needs to be performed for each test on the Lab PN10nm system is the following:

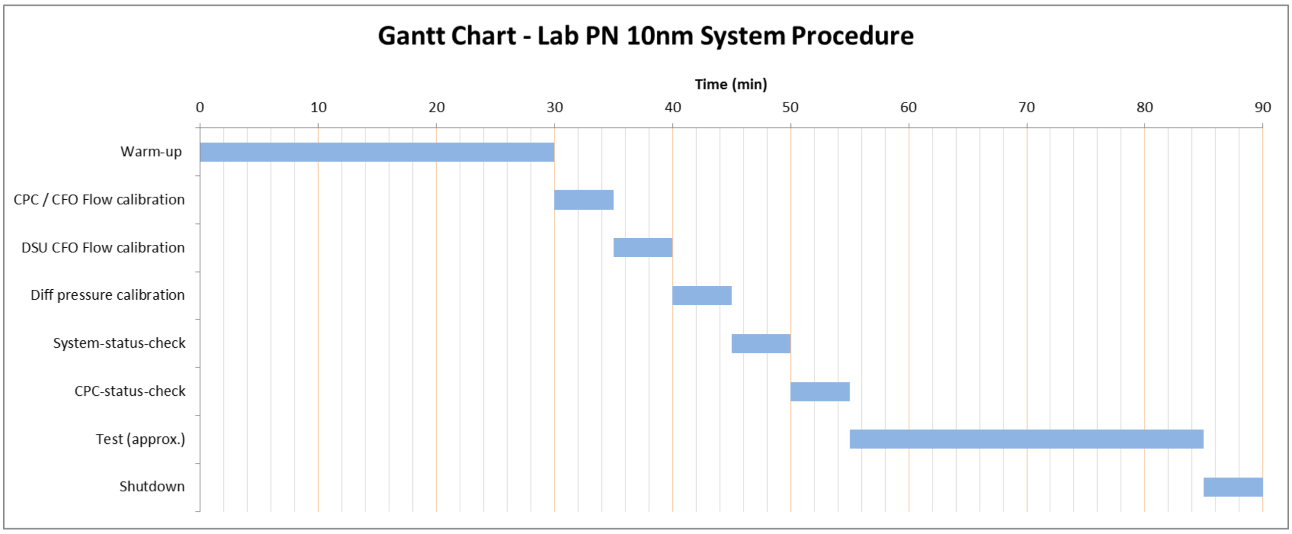

Image 7. Lab PN 10nm system Procedure

6 Measurement Considerations

As mentioned in section 4 of this deliverable, testing will be based on the standard protocols for WLTP, US06 and Artemis 130 (on the chassis dynamometer) and RDE tests (on real road). These procedures will include some emissions measurement designed by the PEMs4Nano project.

The measurements performed will be as follows:

- Bag measurement in g/km of CO, CO2, NOx and PM.
- Second by second (diluted) exhaust emissions measurements of standard gases THC, CO, CO_2 and NOx.
- Second by second Pre/Mid/Post-catalyst (raw) exhaust emissions measurements of standard gases THC, CO, CO_2, NOx and O_2.
- Particle Number (PN) measurement:
    - PN standard measurement of particle number particle size over 23nm by a HORIBA MEXA-2000SPCS (lab PN23nm)
    - PN measurement with the new laboratory system (lab PN10nm)
    - PN standard measurement of particle number particle size over 23nm measurement by the HORIBA PEMS PN (PEMS PN23nm)
    - PN measurement with the new “On-Board” system (PEMS PN10nm)

The testing campaign will be performed on two vehicles selected from the procedure defined in Section 2 after the vehicle preparation and the equipment checking and facilities set-up mentioned in Section 3 and Section 5, respectively.

The tests will be performed according to the test matrix shown in Table 6-1, which details the equipment and configurations used.

Table 6-1. Test matrix

	Tests / Facility	Chassis dyno standard emissions	lab PN23nm	lab PN10nm	PEMS standard emissions	PEMS PN23nm	PEMS PN10nm	Nr of tests/ configuration
Vehicle 1	**WLTC on Chassis Dyno**	x	x	x	x (*) (config A)	x (*)	x (*)	3/config A 1 /config B
	US06 on Chassis Dyno	x	x	x	x (*) (config A)	x (*)	x (*)	3/config A 1 /config B
	Artemis 130 on Chassis Dyno	x	x	x	x (*) (config A)	x (*)	x (*)	3/config A 1 /config B
	RDE on Real Road				x	x	x	3/config C
Vehicle 2	**WLTC on Chassis Dyno**	x	x	x	x (*) (config A)	x (*)	x (*)	3/config A 1 /config B
	US06 on Chassis Dyno	x	x	x	x (*) (config A)	x (*)	x (*)	3/config A 1 /config B
	Artemis 130 on Chassis Dyno	x	x	x	x (*) (config A)	x (*)	x (*)	3/config A 1 /config B
	RDE on Real Road				x	x	x	3/config C

(*) extra-tests, not included in the initial proposal

The three different configurations of the tests mentioned in Table 6-1 are detailed in Sections from 6.1 to 6.3.

6.1 Configuration A

Configuration A will be performed in WLTP, US06 and Artemis 130 cycles performed on chassis dynamometer. Configuration A is shown in Image 8:

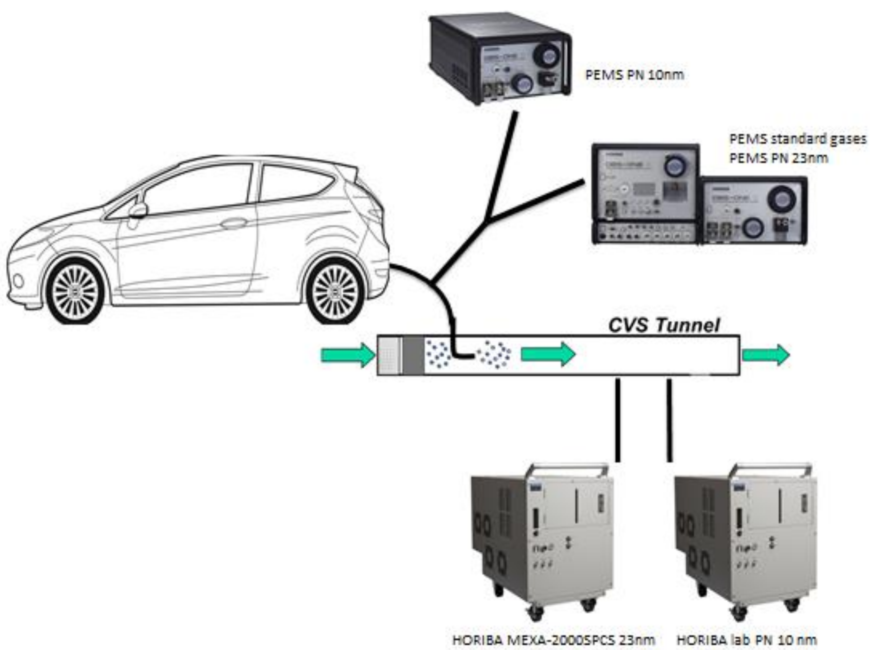

Image 8. Configuration A scheme

In configuration A, PN equipment is mounted in the place designed for this: PEMS PN23 nm and PEMS PN10nm are sampled from the tailpipe using a “Y” piece and lab PN23 nm and lab PN10 nm are sampled from the dilution tunnel independently. The aim of configuration A is to compare the equipment according to its application.

Regarding the configuration and location of the equipment, it has been decided that the SPCS 23nm should not been varied due to repeatability and availability at the test cell for standard certification. Therefore, a Y-Split between both SPCS was not chosen. The PEMS PN system, both 23nm and 10nm device, will be connected throughout the Y-Split because it will be more robust the measure if it is done at the same sample point. In addition, there is less space in the pitot tube for PEMS PN sampling.

6.2 Configuration B

Configuration B will be performed in WLTP, US06 and Artemis 130 cycles on chassis dynamometer.
Configuration B is shown in Image 9:

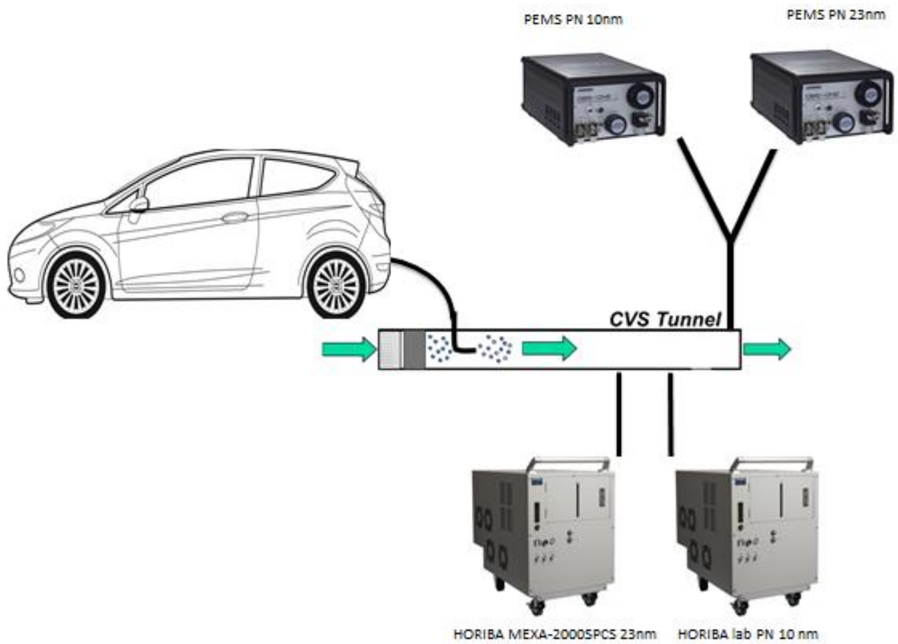

Image 9. Configuration B scheme

In configuration B, PEMS PN23nm, PEMS PN10nm, lab PN23nm and lab PN10nm are sampled from the dilution tunnel to compare the equipment from the same sampling point. In this case, there are some reasons why it has decided not to use the Y-Split between lab PN10nm and PEMS PN10nm system:

- Different flows: lab PN10nm has a 10L/min flow whereas PEMS PN10nm has a flow rate of 0.7 L/min. It might have an influence on PN sampling between both systems.
- Need to minimize amount of configurations of testing campaign in order to test so many test cycles.

- The intention was to compare OBS with OBS and SPCS with SPCS with an amount of uncertainty between lab and OBS system.

6.3 Configuration C

Configuration C will be performed on RDE tests on real road, which is shown in Image 10:

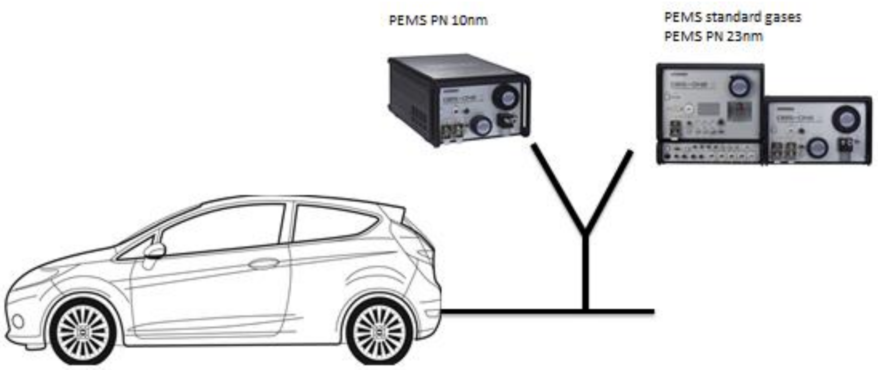

Image 10. Configuration C scheme

In configuration C, PEMS PN10nm and PEMS PN23nm equipment are sampled from the pitot-tube at the tailpipe. The intention is to avoid multiple sampling points; therefore a Y-split has been used.

7 Conclusions

In this deliverable D4.2, the definition of vehicle and testing procedures to be performed on the vehicles, the suggested instrumentation and the most suitable equipment to be used was defined successfully, consisting of how and where to perform the measurements.

The procedure to select the two test vehicles takes into account that these vehicles should cover different range of PN emissions, so should be considered different emission regulations, sizes of engine, PN after-treatment and segments, and also should be in top positions in the top-selling list.

The testing procedures are based on the standard protocols for WLTP, US06 and Artemis 130 (on the chassis dynamometer) and RDE tests (on real road) but with some adaptation to the PEMs4Nano project needs, such as the addition of second-by-second diluted and raw exhaust emissions measurements of standard gases and the measurement of particle number particle size over 10 nm and 23 nm independently.
The WLTP cycle is selected because it was developed using real-driving data, gathered from around the world. WLTP therefore represents better every day driving profiles than NEDC test, which is based on a theoretical driving profile. The combination of the US06 Supplemental Federal Test Procedure and Artemis 130 is selected as a representation of aggressive, high-speed and/or high acceleration driving behaviour, rapid speed fluctuations, and driving behaviour following start-up.

Taking into account the considerations above and after discussions with the rest of PEMs4Nano partners and EU Project Officer, the test matrix was defined to satisfy the needs of the project and it will be used as a basis during the testing campaign.

8 Deviations from Annex 1

The definition of the procedures was discussed with the rest of the partners, and especially the definition of the test matrix was discussed with all PEMs4Nano partners and the EU Project Officer. After these discussions, it was decided:

- to replace the NEDC tests with US06 and Artemis 130 tests because these are more suitable for the Project needs: the US06 Supplemental Federal Test Procedure (SFTP) is selected as a representation of aggressive, high-speed and/or high acceleration driving behaviour, rapid speed fluctuations, and driving behaviour following start-up. Artemis 130 cycle was selected because it is based on statistical analysis of a large database of European real-world driving patterns. This last cycle is also a test with aggressive driving and usually used for R&D projects.

- to add measurements using PEMS PN10nm equipment in the tests performed on the chassis dynamometer in order to compare all the systems in the same tests (configurations A and B detailed in sections 6.1 and 6.2).

These mentioned changes and the additional measurements will be performed without deviation in terms of time or initial budget.

9 Bibliography

[1] European Regulation: Addendum 82: Regulation No. 83 - Annex 4a – Appendix 5(E/ECE/324/Rev.1/Add.82/Rev.5; E/ECE/TRANS/505/Rev.1/Add.82/Rev.5).

2] GTR No. 15: Addendum 15: Global technical regulation No. 15: Worldwide harmonized Light vehicles Test Procedure (ECE/TRANS/180/Add.15).

[3] "European Regulation of Real Driving Emissions (RDE) 2016/46. Additional updated information about the PN 23 nm equipment requirements can be found in the Amending Regulation RDE 4th package.

[4] PEMs4Nano deliverable D2.4 "Calibrated-Solid-Particle-Counting-System-LabUse" - HORIBA Europe

[5] B. Giechaskiel, Real Driving Emissions (RDE): Particle Number (PN) Portable Measurement Systems (PEMS) calibration, EUR 29036 EN, Publications Office of the European Union, Luxembourg, 2018, ISBN 978-92-79-77482-9, doi:10.2760/553725, JRC110424

[6] The HORIBA Solid Particle Counting System MEXA-2100SPCS Instruction manual of Installation and Maintenance.

[7] The HORIBA On-board Emissions Measurement System OBS-ONE-PN 23 nm - Instruction manual of Installation and Maintenance was used to consult some maintenance requirements

10 Acknowledgement

The author(s) would like to thank the partners in the project for their valuable comments on previous drafts and for performing the review.

Project partners:

#	Type	Partner	Partner Full Name
1	IND	HORIBA	Horiba Europe GmbH
2	IND	Bosch	Robert Bosch GmbH
3	IND/SME	CMCL	Computational Modelling Cambridge Limited
4	IND	TSI	TSI GmbH
5	HE	UCAM	The Chancellor, Masters and scholars of the University of Cambridge
6	HE	ULL	Université des Sciences et Technologies De Lille – Lille I
7	IND	IDIADA	IDIADA Automotive Technology SA
8	IND	HORJY	Horiba Jobin Yvon S.A.S.
9	IND/SME	UNR	Uniresearch BV

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Appendix A – Quality Assurance

The following questions should be answered by all reviewers (WP Leader, peer reviewer 1, peer reviewer 2 and the technical coordinator) as part of the Quality Assurance Procedure. Questions answered with NO should be motivated. The author will then make an updated version of the Deliverable. When all reviewers have answered all questions with YES, only then can the Deliverable be submitted to the EC.

NOTE: For public documents this Quality Assurance part will be removed before publication.

Question	WP Leader	Peer reviewer 1	Peer reviewer 2	Peer reviewer 3	Technical Coordinator
	Rosa Delgado	Andreas Manz, Roman Grzeszik	Sebastien Legendre	Philipp Kreutziger	Marcus Rieker
1. Do you accept this deliverable as it is?	Yes	Yes	Yes	Yes	Yes
2. Is the deliverable completely ready? If not, please indicate and motivate required changes.	Yes	Yes	Yes	Yes	Yes
3. Does this deliverable correspond to the DoW?	Yes	Yes	Yes	Yes	Yes
4. Is the Deliverable in line with the PEMs4Nano objectives?	Yes	Yes	Yes	Yes	Yes
a. WP Objectives?	Yes	Yes	Yes	Yes	Yes
b. Task Objectives?	Yes	Yes	Yes	Yes	Yes
5. Is the technical quality sufficient?	Yes	Yes	Yes	Yes	Yes

Appendix B – Abbreviations / Nomenclature

Table B-10-1 List of Abbreviations / Nomenclature.

Symbol / Shortname	
CLD	Chemiluminescence detector
CVS	Constant Volume Sampling
ECU	Engine Control Unit
GDI	Gasoline Direct Injection
GPF	Gasoline Particle Filter
GPS	Global Positioning System
HEPA	High Efficiency Particulate Air
NDIR	Non-dispersive infrared analyzer
PEMS	Portable Emissions Measurement System
PN	Particle Number
RDE	Real Driving Emissions
SPCS	Solid Particle Counting System