Project *Life*-NEEVE:

Innovate technologies to monitor and reduce Non-Exhaust Emission, particles and microplastics of Vehicles and pavements to improve air quality and human health

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Deliverable D2.3:

Design of the initial prototype module on a test bench for monitoring of non-exhaust emissions.

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SUMMARY

This Deliverable describes the methodology used to test an initial prototype of the non-exhaust emissions monitoring module.

The particle measurement instruments used are described, as are the driving cycles used in both laboratory and on-road testing. A summary of the results is also presented.

Finally, the design of the initial prototype configuration of the module is described, with particular attention to the specific components developed during the project.

List of abbreviations and symbols

In this Deliverable abbreviations or symbols in the table below are often used.

Abbreviation	Explanation	Comment
Partners, companies or institutions related to this project		
CEN	European Committee for Standarization	
TSI		Instruments manufacturing company
UNECE	United Nations Economic Commission for Europe	
WHO	World Health Organization	
Technical terminology		
CAD	Computer-Aided Design	
CPC	Condensation Particle Counter	
EDS	Energy-Dispersive X-ray Spectroscopy	
EEPS	Engine Exhaust Particle Spectrometer	Trademark
ELPI+	Electrical Low-Pressure Impactor	Trademark
IR	Infrared	
LDV	Light-duty vehicle	
NEDC	New European Driving Cycle	
NEE	Non-Exhaust Emissions	
OBD	On-Board Diagnostics	
OBS	On-Board emissions measurement System	Trademark
OEM	Original Equipment Manufacturer	
OPS	Optical Particle Sizer	
PC	Personal Computer	
PEMS	Portable Emissions Measurement System	
PM	Mass Particle concentration	
PM10 / 2.5 / 1	Mass Particle concentration with less than 10 / 2.5 / 1 micrometre diameter	
PN	Number Particle concentration	
PSD	Particle Size Distribution	
RDE	Real Driving Emissions test cycle	
SEM	Scanning Electronic Microscopy	
TEM	Transmission Electronic Microscopy	
WLTP	Worldwide Harmonised Light-duty Test Procedure	
Measures and units		
μm	Micrometre	
Cm	Centimetre	
Hz	Hertz	
Kg	Kilogram	

L	Litre	
m	Metre	
min	Minute	
mm	Millimetre	
nm	Nanometre	
s	Second	
t	Ton	

Table of contents

1. INTRODUCTION 1

2. PURPOSE AND OBJECTIVES 1

3. EXPERIMENTAL METHODOLOGY 2

3.1. Test environments 3
  3.1.1. Dynamometer Test Bench 3
  3.1.2. On-Road Tests 3

3.2. Driving cycles 4

3.3. Measurement equipment 8

4. RESULTS OF THE NON-EXHAUST EMISSIONS (NEE) MEASUREMENT SYSTEM 14

5. CONCLUSIONS 16

6. DESCRIPTION OF THE FIRST PROTOTYPE MODULE 17

7. ACKNOWLEDGEMENTS 20

8. REFERENCES 20

Life

1. Introduction

Exhaust emissions from the tailpipe of vehicles, including particulate matter, have been a concern since many years ago. Progressively more stringent regulations on exhaust emissions have been put in place [European Parliament, 2007]. Correspondently, appropriate standards have been established for testing particulate matter in exhaust emissions from vehicles' tailpipes [UNECE, 2014, European Commission, 2017, European Commission, 2023]. These standards cover official type approval emissions tests.

As new techniques were implemented on vehicles, exhaust emissions were progressively reduced. Thus, non-exhaust emissions (NEE) are becoming a relevant source, even the dominating one depending on the metric used. Some studies found that they constitute 73% (by mass) of PM10 emissions from road transport [Defra, 2019]. Growing public awareness about microplastics has also played a role in raising interest on particle emissions from tyres wear. Future regulations, currently under elaboration, will set limits on NEE [European Commission, 2022].

Standard test procedures for laboratory measurement of brake emissions from Light-Duty Vehicles (LDV) have been published recently [UNECE, 2023]. Standard procedures for determination of tyre abrasion are also expected soon from UNECE. However, these will only determine tyre weight loss with use and not concentration or granulometry of emitted particles.

A measurement system must offer a high degree of repeatability, as well as results that are as representative as possible of particle emissions.

2. Purpose and objectives

One of the objectives of Life NEEVE project is to design and develop a real-time on-board measurement system to monitor NEE.

To that end, Task T2.3 objective was the design and adjustment of an initial prototype module for real-time measurement of NEE. The work has been carried out considering the data obtained in Task T.2.2 (State of the Art analysis), and performing the operation tests on a chassis dynamometer test bench and also in real driving tests. The Deliverable D2.2 reviewed the state of the art in non-exhaust emissions measurement methods, serving as a starting point for the development work of the initial prototype module. CIEMAT designed and tested the new initial prototype measuring module with technical advice from HORIBA.

The design was developed taking into account experience in previous works, in such way that temperatures, sampling pipes and surface materials of each component, line length and diameter, flow rates, characteristics of diluters, characteristics of cyclonic separators and all relevant parameters which may influence the sample composition were selected according to our best judgement. The aim was to minimise negative impacts, such as particle losses, agglomeration, condensation or volatilization.

The purpose of Deliverable D2.3 is to describe the first prototype module, and the results obtained in the first laboratory tests on a chassis dynamometer test bench.

3. Experimental Methodology

A series of tests were undertaken with the initial prototype module installed in cars on a dynamometer test bench. Also, a series of on-road tests under a set of different real-world braking conditions were done.

During the tests, real-time NEE particle concentration and PSD were recorded as measured by the instruments installed in the module. Temperature profiles in the braking system of the vehicle, operating data of the dynamometer test bench, operating data of the vehicle taken through the OBD interface and GPS location and velocity data were also recorded. Additionally, PM samples were taken during certain tests on membrane flat filters. These samples were then examined using SEM and TEM microscopy and EDS analysis.

Two different cars were selected for the tests, a Skoda Yeti and a Nissan Leaf. These cars were chosen for the tests as examples of passenger vehicles equipped with combustion and electric engines, respectively.

The vehicles' brake system components (brake pads and disks) used during the tests were the original equipment manufacturer (OEM). Pads and disks were subjected to analysis that identified iron, copper, and aluminium, among the materials used in the manufacture of these components.

Tyres used in the tests were of summer type in the approved sizes for the used vehicles. Namely 225/50/R17 for the Skoda and 205/55/R16 for the Nissan. Tyres were almost new.

To gain information about the brake system's performance and the effect of the brake temperature on particle emissions concentration and physicochemical properties, temperature profiles were measured at various critical locations.

To this end, type K thermocouples, with an accuracy of ± 1°C within the range of −200 to 1372 °C, were used. These thermocouples were integrated into the brake pads, brake calliper, and brake disk. Temperature data was recorded at a rate of twice per second, ensuring monitoring of the thermal behaviour of the brake components during operation.

The K-type thermocouple specifically designed for brake disks was mounted onto the disk using a custom-designed set of plates that were attached to the vehicle's control arm (suspension arm). This setup allowed the thermocouple to remain in firm contact with the disk's surface, ensuring temperature measurements during rotation while minimizing any interference with the braking performance. The thermocouple was positioned at the centre of the disk to capture representative temperature data.

NEE aerosol samples were taken through a probe located in the wheel hub of one of the front wheels of the vehicle. The sampling position was selected to provide a direct path from the brake to the sampling tube, minimizing particle loss.

A circular polycarbonate lid was installed on the outer side of the wheel, covering the area within the rim. This lid serves as an isolator that minimizes potential environmental interference, ensuring that the particles measured come directly from the brake system.

Additionally, the brake system's inherent design provides a degree of shielding from environmental interference from the inner side of the wheel and brake assembly, limiting the ingress of external particles. Moreover, an in-house device, provisionally named NEEVE Emissions Cover, was specifically designed and manufactured to be attached to the car's rim, to improve NEE sampling.

3.1. Test environments

During this phase of the project, a series of tests were conducted both on a chassis dynamometer and on-road under real-world driving conditions to validate the functionality of the initial prototype designed for measuring non-exhaust particle emissions (NEE).

3.1.1. Chassis Dynamometer Test Bench

A chassis dynamometer is used to simulate real-life driving conditions while the vehicle remains stationary. It is used in automotive laboratories for testing engines, transmissions, emissions, and other vehicle systems.

It consists of the following main components: rotating rollers, loading system, ventilation system and sensors, electronics and control software. The rotating rollers are metal cylinders that hold the vehicle's drive wheels. The loading system apply resistance to the vehicle's movement to simulate real-life driving conditions. The ventilation system, normally a fan placed in front of the vehicle, simulates airflow to cool the engine, similar to real-life driving. Sensors and electronics measure variables such as speed, torque, power, emissions, temperature, etc.

For the tests a single-axle MAHA FPS 2700 test bench was used. This dynamometer bench is suitable for passenger cars and vans with axle loads of up to 2.7 t. The FPS series is used to test vehicles with a maximum standard engine power of 260 kW and a maximum test speed of 200 km/h. It is automatically controlled through a PC. Among other tests, it can carry on driving cycle simulations, such as the WLTP and NEDC cycles.

For the tyre wear tests, the test bench rolls were wrapped in anti-slip tape. The intention was to increase the friction between the rolls and the tyre, and to provide a more abrasive surface than the bare steel roll.

Tesa 60950 anti-slip adhesive tape was used. The anti-slip tape comprises an adhesive PVC substrate coated with mineral particles. Adhesion force to steel is 5.8 N/cm, and the tape thickness is 720 μm.

3.1.2. On-Road Tests

Further to the tests on the dynamometer on-road emissions tests were also conducted. These tests were intended to measure the actual NEE from a vehicle while driving on real roads, as opposed to in a controlled laboratory setting. This type of test provides a more accurate representation of the environmental conditions and surrounding traffic impact on a vehicle's emissions.

Real-life driving conditions include a number of factors that are difficult to reproduce on a dynamometer test bench. These factors may influence both NEE emissions and the performance of the measuring equipment. A brief enumeration of some of them is listed below.

- Influence of vibrations from the engine, shocks from bumps on the road, etc. on the performance of measurement instrumentation.
- Interference from other sources such as surrounding traffic, for instance.
- Influence of different road surfaces such as concrete, tarmac, dirt track, etc. on NEE
- Influence of the condition of the road surface on NEE. A wet or icy surface or the degree of surface cleanliness could influence emissions
- Influence of climatological conditions, in particular rainy or windy weather for example.

3.2. Driving cycles

During the tests three standard driving test cycles were used, namely the New European Driving Cycle (NEDC), Worldwide Harmonized Light Vehicles Test Procedure (WLTP) and the Real Driving Emissions (RDE) test cycle. Descriptions of these cycles may be found on the literature [Liu, 2020, Ligterink, 2016, Zardini, 2020]. Figure 1 through Figure 4 show the profile of WLTP cycle.

Until 2018, NEDC was used in the European Union. It became obsolete due to the difficulty of making precise calculations. In other words, it couldn't determine how polluting a car could be due to the introduction of models with more complex engines.

It focused on driving conditions at speeds of 120 km/h and above. The main problem was that it didn't take into account pollution within built-up areas, only on interurban roads.

As of September 2019, the NEDC was replaced by the WLTP [UN, 2019]. The WLTP has introduced much more realistic testing conditions, including a more realistic driving involving harder acceleration and more time at high speeds, as well as stricter car set-up and measurement conditions.

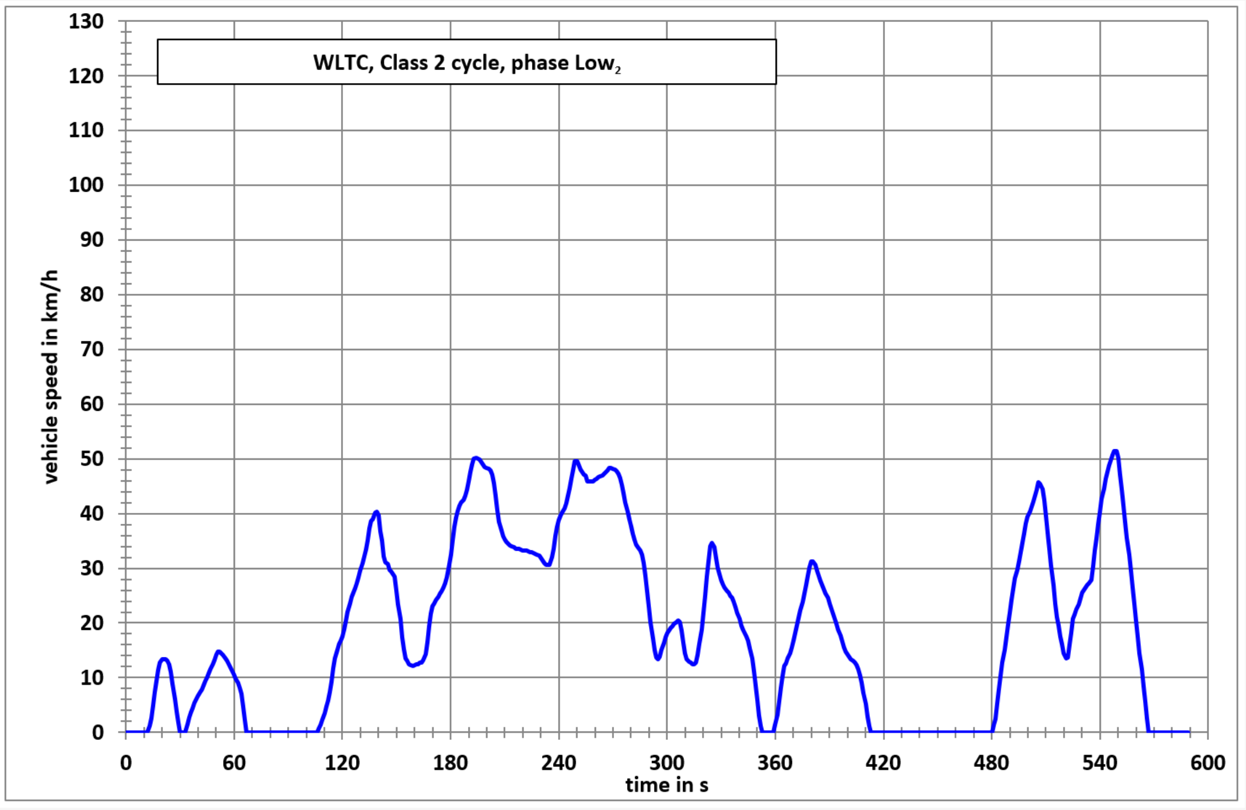

Figure 1 WLTP test cycle, phase Low

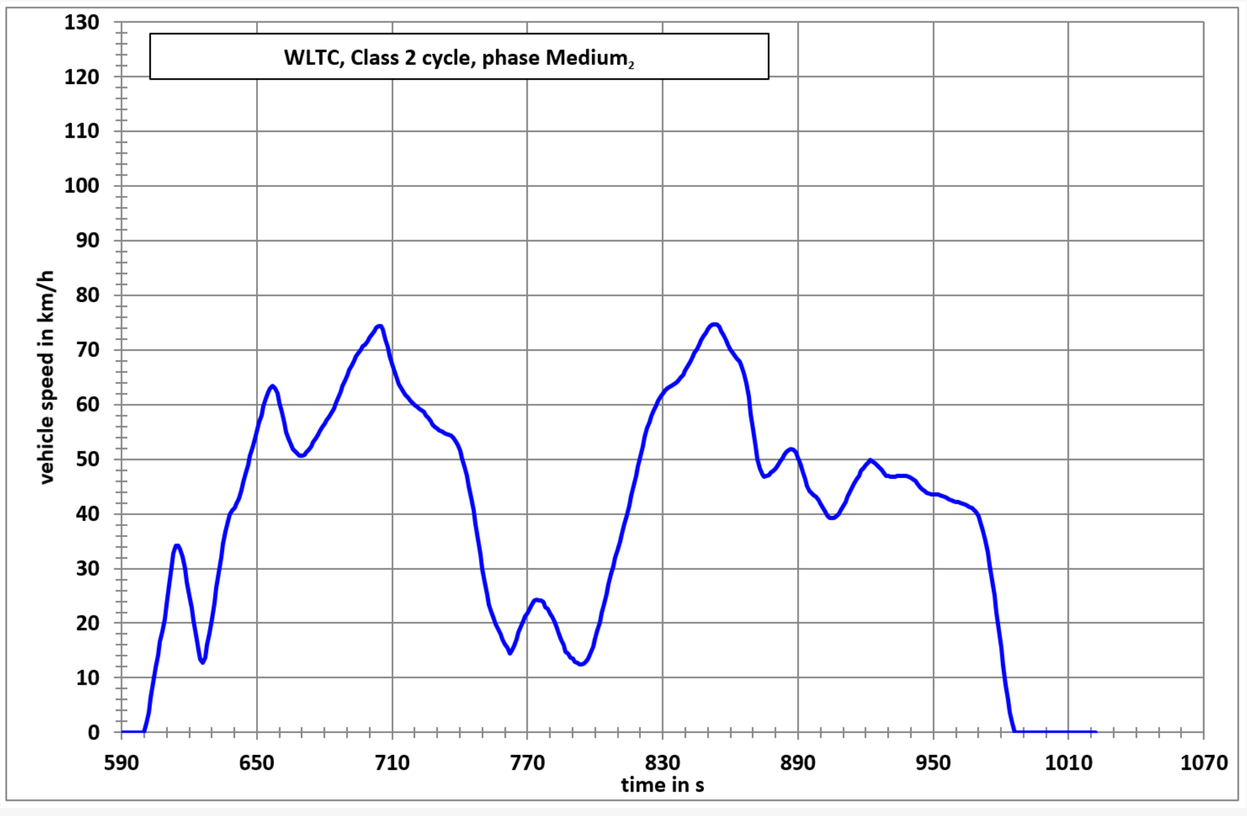

Figure 2   WLTP test cycle, phase Medium

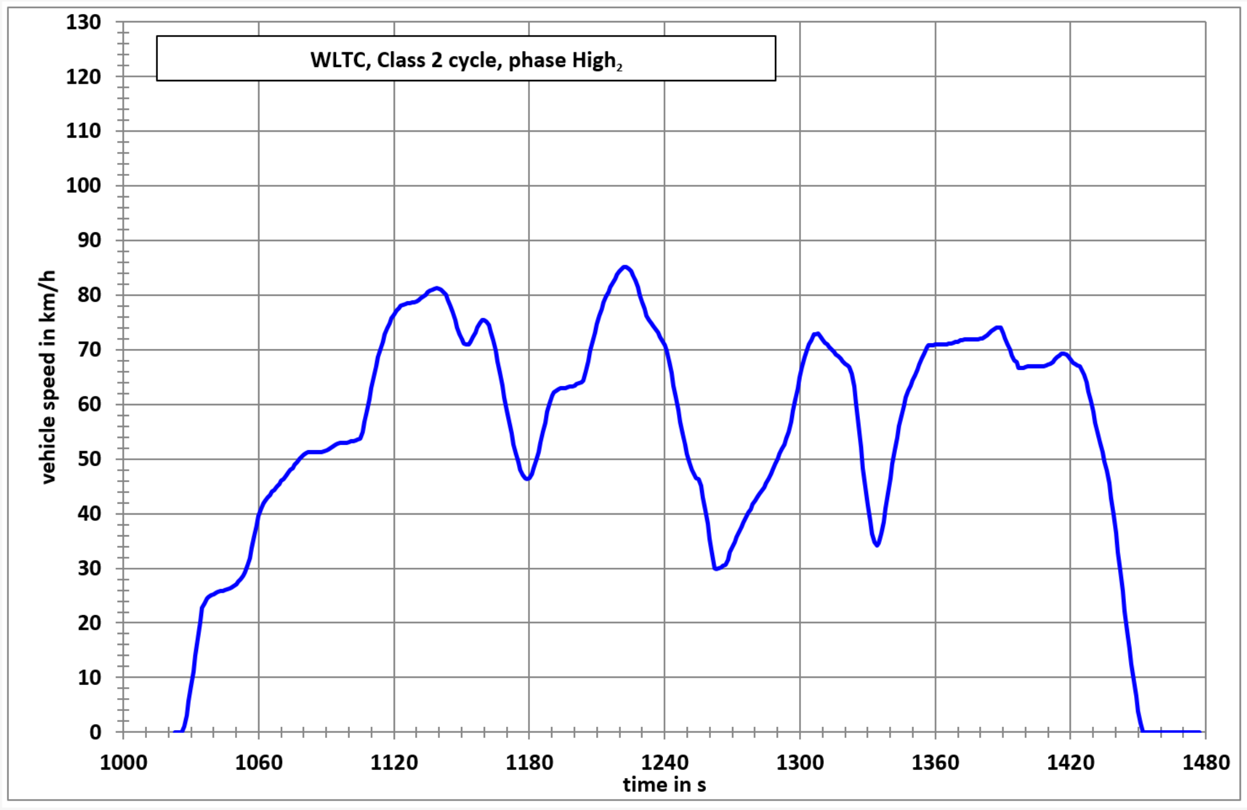

Figure 3 WLTP test cycle, phase High

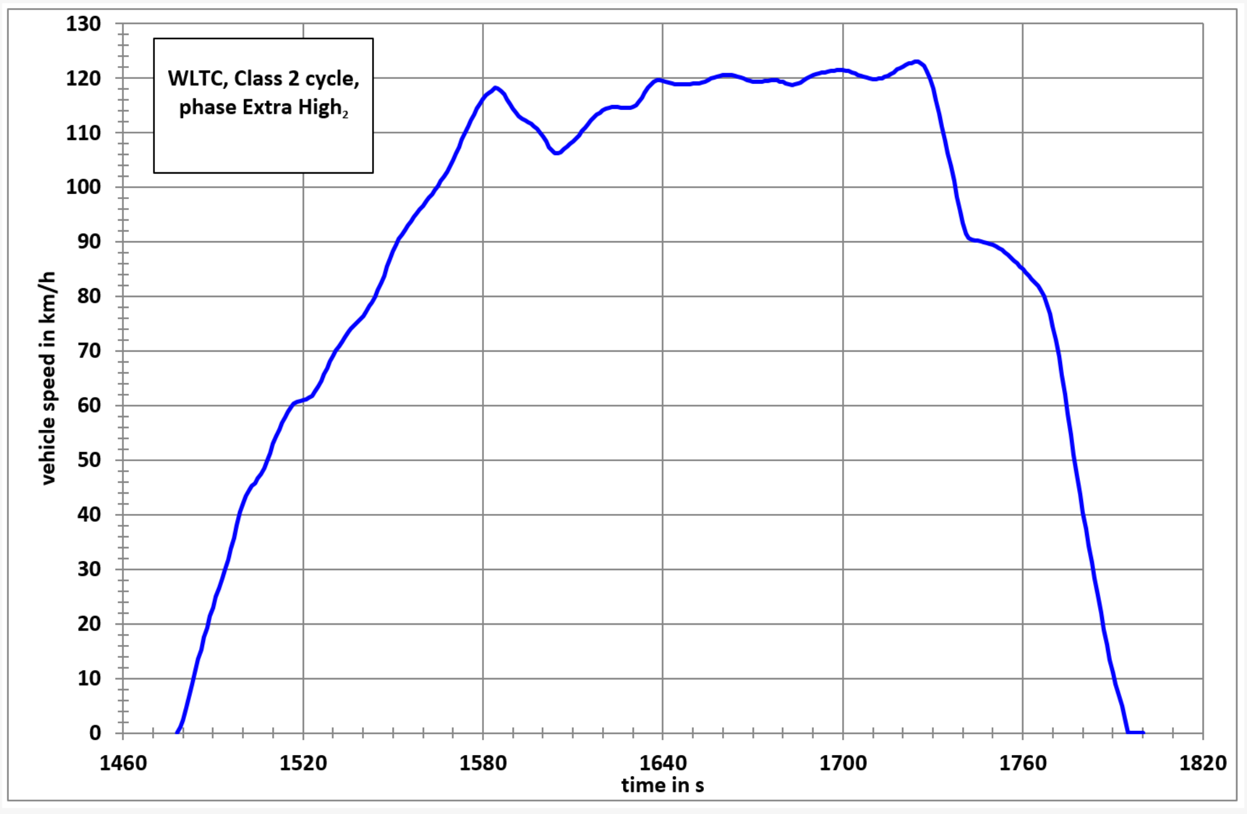

Figure 4 WLTP test cycle, phase Extra High

The latest Euro 6 standard brought more stringent requirements in vehicle emission control in Europe including the RDE test. The most widely known method for RDE testing, involves the use of certified mobile measurement equipment known as Portable Emissions Measurement System (PEMS).

NEDC, WLTP and RDE driving cycles were developed with exhaust tailpipe emissions and fuel economy measurements in mind. So, it was decided to additionally use two in-house cycles, one each specifically aimed for brake and tyre wear originated particles. These cycles will be referred to as “hot braking” and “speed intervals” cycles in the following.

The “hot braking” cycle simulates harsh braking conditions, allowing for the evaluation of brake system performance and associated emissions in critical situations [Al Wasif, 2025]. This choice is crucial because harsh braking can significantly impact the generation of brake wear particles.

The test is termed “hot” because, prior to the actual braking events, the brake system is preheated to over 250 °C. This preheating replicate demanding braking scenarios, such as continuous braking on steep downhill roads, heavy stop-and-go traffic, or emergency stops at high speeds, where brake temperatures can rise significantly.

The speed sequence followed during the preheating process was as follows: three braking events from 60 to 0 km/h in 8 s, three from 80 to 0 km/h in 8 s, three from 100 to 0 km/h in 8 s, and finally, three from 120 to 0 km/h in 8 s. Once the brake system was heated, the measurements under the “hot braking” cycle began. This cycle involved repeating the same conditions used in the preheating process, measuring the particles emitted during those braking events and reaching a maximum disk temperature of 380 °C.

Regarding the “speed intervals” cycle, it comprises five stints at different speeds, five minutes long each. The speeds selected are 40, 60, 80, 100 and 120 km/h.

Table 1 shows the cycles used in each of the test scenarios.

Table 1 Driving cycles used in the tests

	On-road	Dynamometer test bench
Brakes wear	In-house “hot braking” cycle RDE	
Tyres wear		NEDC WLTP In-house “speed intervals” cycle

3.3. Measurement equipment

Due to the varied mechanisms that generate them, NEE emissions comprise particles of a wide size range [Alemani, 2016, Piscitello, 2021], covering several orders of magnitude. Moreover, NEE particle size and number may change rapidly, particularly during braking and acceleration events. In order to capture these rapid changes, measurement equipment should also be able to perform real-time measurements.

In order to achieve the objective to determine both the total concentration of particles and their particle size distribution, both the measurement techniques and the metrics used to express the results must be tailored to different particle size ranges.

Bearing in mind these requirements, four real-time measuring instruments were selected. Three of them, TSI Engine Exhaust Particle Sizer Spectrometer (EEPS), TSI Optical Particle Sizer (OPS) and Dekati Electrical Low Pressure Impactor (ELPI+), are able to measure PSD in different size ranges. The fourth instrument, Horiba OBS-One PN, measures total particle number concentration in real-time. *Table* ***2*** summarises some characteristics of these instruments.

Table 2 Some selected characteristics of measuring instruments used in the experiments

Instrument	Particle size range	Particle concentration range	Measuring rate	Measuring principle	Notes
EEPS 3090 (TSI)	5.6 – 560 nm	1,000 – 1×10⁹ #/cm³	10 Hz	Electrical mobility	Requires a minimum concentration, low upper size range limit

OPS 3330 (TSI)	0.3 – 10 µm	0 – 3,000 #/cm³	1 Hz	Light scattering	Low upper concentration range limit
ELPI+ (Dekati)	6 nm – 10 µm	Not specified (estimated to be 5×10^7 #/cm³)	10 Hz	Inertia	Low size resolution (14 channels), vacuum pump required,
OBS-ONE PN (Horiba)	23 – 1,000 nm	0 – 5×10^7 #/cm³	real time	Condensation particle counter	Does not provide particle size distribution

The EEPS spectrometer sizes particles according to their electrical mobility, while OPS sizes particles according to their optical properties and ELPI+ does it according to their aerodynamic equivalent diameter (i.e. inertia).

Instruments based on electrical mobility are currently the most widespread used for size measurement of submicron-sized particles. The differential mobility analyser was introduced by [Knutson and Whitby, 1975]. It scans the voltage applied to the classification region to acquire the particle size distribution (PSD) in a few minutes. Non-scanning mobility spectrometers employ multiple detectors to simultaneously measure mobility-separated particles and acquire PSDs at 0.1–1 s intervals.

Instruments based on light scattering by single particles have been used for real time counting and sizing of aerosols for a long time. Different combinations of light sources (white or monochromatic) and scattering angles (forward, 90º, etc.) have been proposed [Xu, 2015], in an effort to reduce the influence of the particles' optical properties (absorption, refractive index) on the response function of the instrument. This kind of instruments are generally suitable for particles with diameters above 0.5-0.7 micrometres.

Cascade impactors separate particles into size classes as a function of their inertia [Marple, 2004]. Low pressure cascade impactors, such ELPI+ [Järvinen, 2014], are able to provide PSD over a wide size range, from several micrometres down to a few nanometres. Their downside is a low size resolution, as they typically feature about 10 channels. Another drawback can be the necessity to carry a vacuum pump that can be noisy, heavy and a source of vibrations.

TSI Engine Exhaust Particle Sizer (EEPS) 3090

The Engine Exhaust Particle Sizer™ (EEPS; Model 3090, TSI) is a non-scanning mobility spectrometer [Johnson, 2004] based on the initial design of [Tammet, 2002]. It was originally intended for exhaust emissions measurement during transient test cycles and other fast non-steady processes. It is also suitable for real time NEE measurement.

The instrument draws the sample through a cyclone at the inlet that prevents particles larger than 1 µm from entering the EEPS. The sample is successively exposed to negative and positive corona discharge ionizers to bring it to a predictable charge distribution. The sample is then transported down the classification region, together with filtered sheath air (Figure 5). This region is bounded by a central positive high-voltage electrode column and an outer cylindrical wall. A series of electrometers is disposed on the outer wall. The electric field repels the positively charged particles outward according to their electrical mobility.

Charged particles strike the respective electrometers, according to their mobility, and transfer their charge. This arrangement allows for simultaneous concentration measurements of multiple particle sizes. EEPS measures particle size from 5.6 to 560 nm at 10 Hz to visualize the dynamic behaviour of particle emissions.

Due to the background noise of the electrometers, a minimum particle concentration is required to perform measurements. Different data inversion matrices allow to optimize size distribution accuracy for specific particle types (soot, default and compact).

EEPS' main characteristics are as follows:

- Sample flow rate   10 L/min
- Size range: 5.6 - 560 nm in up to 32 channels
- Wide concentration range from 0 to 3 000 particles/cm^3
- Operational sample temperature 10 – 52 ºC
- Minimum particle concentration   1 000 particles/cm^3
- Maximum particle concentration   1 10^9 particles/cm^3

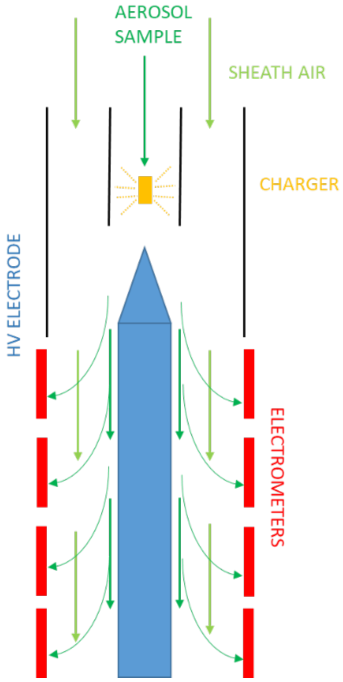

Figure 5 Schematic diagram of EEPS operation

TSI Optical Particle Sizer (OPS) 3330

TSI's OPS uses single particle counting technology to measure particle concentration and size distribution from 0.3 to 10 µm in 16 user adjustable size channels. Measurements are registered once per second (1 Hz).

Particles are individually counted and sized when they enter a sensing volume defined by the instrument's optics (Figure 6). Number particle concentration is directly determined, while mass concentration can be derived if particle density is known or assumed.

Particle size is inferred from the intensity of the pulse of scattered light, using the Mie scattering theory. The lower limit of the measuring size range is imposed by the wavelength of the source of light used (a laser diode), whereas the avoidance of coincidence errors (when two particles enter the sensing volume simultaneously) impose a limit on particle concentration. A sheath flow surrounds the sample, focusing the aerosol to enhance size resolution, and keeping the optics clean for improved reliability and low maintenance. Optical properties of the aerosol, such as refractive index and shape factor, can be entered for most accurate size distribution data as well as improved particle mass concentration output. The measured particles can also be collected on a built-in 37 mm filter for further analysis.

OPS' main characteristics are as follows:

- Sample flowrate 1 L/min
- Size resolution < 5 % at 0.5 µm
- User adjustable size channels
- Size range: 0.3 - 10 µm in up to 16 channels
- Concentration range from 0 to 3 000 #/cm^3
- Operational temperature 0 – 45 ºC
- Displays particle number concentration and particle mass with the ability to input refractive index and particle density
- Filter-based sample collection for later gravimetric or chemical analysis
- Battery-powered for up to 12 hours of operation
- Built-in data logging capability for up to 30 000 samples

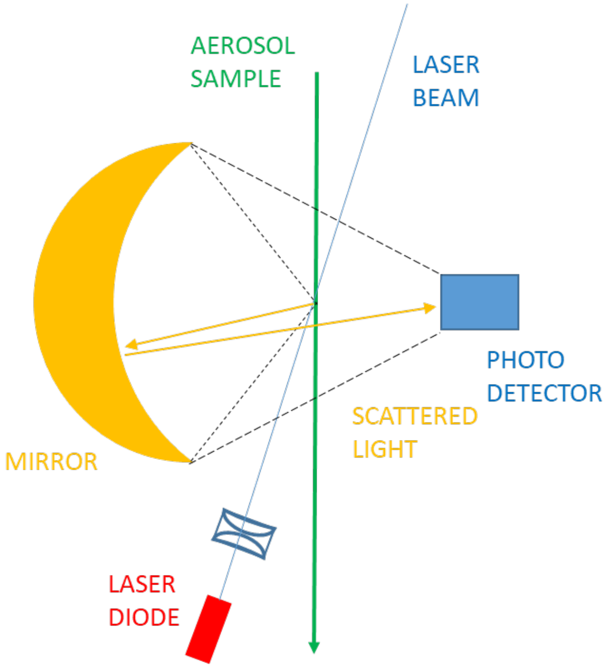

Figure 6 Schematic diagram of OPS operation

HORIBA OBS-ONE PN

The OBS-ONE PN unit is an on-board emissions measurement system for real-time measurement of particle number concentration in the 23 – 1 000 nm particle size range under real-world driving conditions. The unit uses a condensation particle counter which is recommended principle by the Particle Measurement Programme (PMP), one of working groups affiliated with UNECE. Originally developed for tailpipe emissions, the lower limit of the size range was adjusted at 23 nm as to avoid detection of non-solid particles produced by condensation of semi-volatile compounds.

OBS-ONE PN's main characteristics are as follows:

- Sample flowrate: 0.7 L/min
- Size range: 23 nm - 1 µm
- Concentration range from 0 to 5 10^7 #/cm^3
- Operational temperature -10 – 40 ºC
- Working fluid: Isopropanol

Dekati Electrical Low Pressure Impactor (ELPI+)

The Dekati ELPI+ enables measurement of real-time particle size distribution and concentration in the size range of 6 nm – 10 µm at 10 Hz sampling rate. First, a unipolar corona charger is used to charge the particles up to a known positive charge level. Then, they are size classified in a low pressure cascade impactor into 14 size classes depending on their aerodynamic size. Each of the impactor stages is electrically insulated and connected to an electrometer (Figure 7). The measured current signal from the electrometers is used to measure particle number size distribution and concentration in real-time.

One particular advantage of ELPI+ is that the measurement method is the same for all the particle sizes, covering a broad particle size range using only one measurement technique.

ELPI+ main characteristics are as follows:

- Sample flowrate: 10 L/min
- Sample temperature: 10-50 ºC
- Size range: 6 nm – 10 µm
- Sampling rate: 10 Hz
- 14 particle size fractions, 500 channels PSD can be inferred by software
- Possibility to collect size classified particles for chemical analysis using analysis collection plates

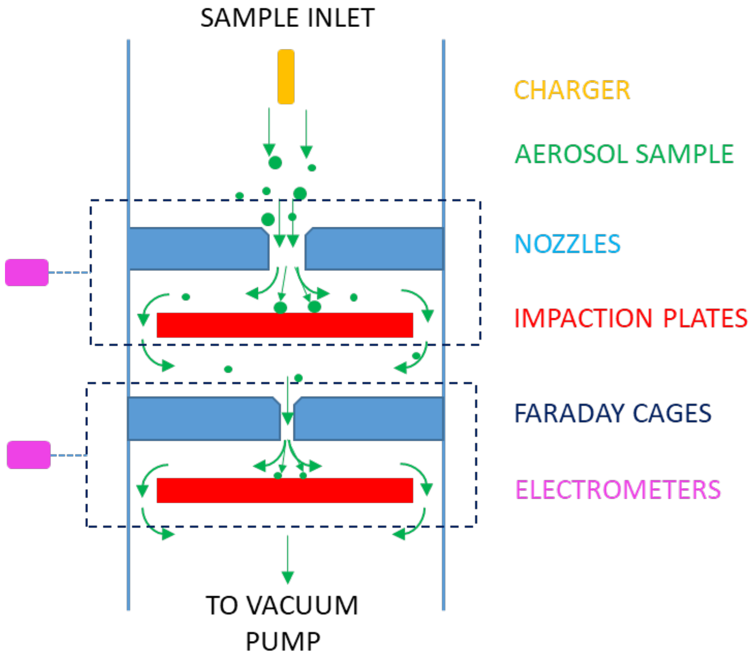

Figure 7 Schematic diagram of ELPI+ operation

Auxiliary Instrumentation

Besides particle measuring instruments, some other instruments were used to monitor additional test parameters.

A handheld IR thermometer (Fluke 62 MAX) was used for remote temperature measurements. The measuring range is -30 °C to 500 °C, with ±1.5 % accuracy. A small thermal imaging camera

(HIKMICRO MiniE) was also used. This convenience camera can be mounted on the USB-C port of any smartphone. Its measuring range is -20 °C to 400 °C, with ±2 % accuracy.

A universal wireless OBD adapter (OBDLink LX Bluetooth) was used to acquire and relay the test vehicle operating data. This adapter supports all OBD-II protocols. Sometimes a wired adapter (OVCDS 16.9) was used instead. This adapter is specific for VW Group vehicles.

4. Results of the Non-Exhaust Emissions (NEE) Measurement System

Table 2 summarizes the different tests performed, including the test environment, driving cycle, instruments used, and the maximum particle concentrations detected.

The tests focused on tyre wear, carried out on the test bench using standard cycles (NEDC and WLTP) and a custom speed-interval cycle, showed maximum particle concentrations on the order of 10^5 particles/cm³. These values confirm the system's ability to detect variations in particle emissions based on speed and applied load, as well as the robustness of the selected instruments (EEPS, OPS, ELPI+) for capturing wide size and concentration ranges.

Regarding brake wear tests, on-road tests were performed. Particularly relevant were the results from the “hot braking” cycle, which simulates harsh decelerations from speeds between 60 and 120 km/h. Under these conditions, concentrations up to 10^6 #/cm³ were recorded, especially during braking events from 120 km/h, where brake disk temperatures exceeded 370 °C. This behaviour highlights a strong dependence of emissions on brake temperature, as also reported in the accompanying scientific article [Al Wasif-Ruiz, 2025]. That study confirmed that the emitted particle size distribution during braking varies with initial vehicle speed, and hence with the thermal energy released during deceleration.

In addition to real-time measurements of concentration and size distribution using EEPS, OPS, and ELPI+, particle samples were collected on filters for subsequent morphological and compositional analysis using SEM/TEM and EDS. The collected particles showed different morphologies —from irregular aggregates to spherical forms— depending on the temperature reached during braking. Elemental composition mainly included iron, copper, and aluminium, confirming that the particles originated from the wear of brake discs and pads.

Table 3 Summary of tests

Test Reference	Environment	Driving Cycle	Instruments	Maximum Particle Concentration	Remarks
Tyres_TB_NEDC	Test Bench	NEDC	EEPS / OPS / ELPI+	10^5 #/cm^3	
Tyres_TB_WLTP	Test Bench	WLTP	EEPS / OPS / ELPI+	10^5 #/cm^3	
Tyres_TB_speed intervals	Test Bench	Speed Intervals	EEPS / OPS / ELPI+	10^5 #/cm^3	
Brakes_OnBoard	OnBoard	Hot Braking (60→0 / 80→0 / 100→0 / 120→0)	EEPS / OPS / OBS-ONE PN	10^7 #/cm^3	OPS was used but did not operate correctly due to sensor saturation.
Brakes_OnBoard_RDE	OnBoard	RDE	EEPS / OPS / ELPI+	10^4 #/cm^3	ELPI was used but did not operate correctly according to supplier feedback.

It is also important to highlight that the system was successfully tested on a fully electric vehicle (Nissan Leaf), demonstrating that the measurement module is compatible with alternative propulsion technologies. This validation is especially relevant given the increasing presence of electric vehicles in urban areas, and the need to quantify NEE emissions regardless of the powertrain.

It should be noted that some technical limitations were encountered during specific tests, such as sensor saturation with the OPS and malfunction of the ELPI+ under field conditions. These issues, recorded in the results table, will guide future improvements in system design, instrument selection, and the establishment of robust calibration and maintenance protocols.

In conclusion, the results obtained at this stage validate the performance of the initial prototype across a broad range of conditions and lay the groundwork for its further development into an operational system. This system could be deployed in real-world NEE monitoring campaigns, with potential applications in both scientific research and future regulatory frameworks.

5. Conclusions

Particle NEE not only cover a wide range of sizes, but they also comprise materials of very different nature, from organic compounds to minerals and rubber. These materials differ in many properties such as density, refractive index, electrical properties, etc. These differences should be taken into account when selecting measurement instruments and adjusting their settings and data deconvolution methods. Particle density, in particular, is crucial if conversions between number and mass concentration are undertaken.

It is important to note that NEE particles differ from engine exhaust particles in many properties. As a result, instruments used so far for exhaust emissions measurement could need to be readjusted. Some aspects to be considered could be as follows:

- EEPS: select the proper inversion matrix or develop a new one
- OPC (or similar optical instruments): select proper refractive index
- CPC: establish appropriate lower size range threshold
- ELPI+: select proper value of particle density

Transfer lines are not expected to need heating, since NEE do not contain semi-volatile compounds and, although they originate in high temperature processes in some cases, rapid dilution with ambient air make their temperature drop very quickly before collection.

Dilution may be needed in order to use certain instruments (OPC) that have a low maximum concentration capability.

Electronic microscopy examination has shown that NEE particles present a compact shape, contrasting with the fractal structures typical of soot particles.

Careful attention should be given to sample splitting in the transfer section, given that NEE contain coarse particles with considerable inertia. Proper sample splitters should be used to prevent losses or unequal division of the PM in the sample.

Standard dimensions (length and diameter) of transfer lines should be established in order to achieve comparable results across different car models, etc. While it is desirable to keep the lines as short as possible, transfer lines should be long enough to allow installation of the measurement module in any light-duty vehicle.

A lower threshold limit to the particle size range should be selected, same as was done for engine exhaust solid PN emissions (23 nm). Potential differences in nature between exhaust and non-exhaust particle emissions advice caution before adopting the same limit as for exhaust emissions. A recent air quality monitoring method [CEN, 2024] sets a 10 nm lower limit to the size range for ambient total PN measurement.

The wide size range encompassed by NEE particles will probably need two different instruments to cover. While PM is dominated by coarse particles, PN is dominated by ultrafine particles. PM10 and PM2.5 air quality standards are based on mass concentration metric. On the other hand, WHO has recently recommended PN for ultrafine particles monitoring in ambient air [WHO, 2021]. So, implementing both PN and PM concentration measurement in the prototype module is necessary.

Using an instrument measuring number concentration in the prototype module for coarse particles monitoring is problematic, since deriving mass concentration from number concentration data is prone to errors due to uncertainties in particle density value.

6. Description of the first prototype module

The first prototype module is made up of three sections: the collection section, the transport and conditioning section, and the measurement section. Although, so far, measurements have been done using one separate sampling line for each instrument, a new proposed transport and conditioning section is described in the following.

The collection section function is to take a representative sample of the emitted particles.

The transport and conditioning section, in turn, transports this sample to the measuring instruments. This process must prevent or minimize sample alterations, which would lead to errors in determining its concentration and particle size distribution. These alterations occur through the processes of particle agglomeration and deposition. Particle loss due to deposition, in turn, can be caused by gravitational mechanisms, Brownian diffusion, thermophoresis, electrostatic forces, etc.

Sample conditioning is usually necessary, normally involving dilution. This reduces its concentration and temperature. The reduction in concentration and temperature prevents sample alterations and adjusts these parameters to the operating ranges of the measuring instruments. Dilution also reduces the partial pressure of vapours, preventing condensation. Condensation would be detrimental in a number of ways, it produces new particles, enhances agglomeration, harms measuring instruments, etc.

Finally, the measurement section consists of the measuring instruments themselves, which determine the concentration and particle size distribution of the aerosol.

The collection section comprises a device specifically designed for the NEEVE Project, it is a collection device that allows the controlled collection of particulate matter generated by friction. This component, called the NEEVE Emissions Cover (Figure 8), has been developed as a modular solution adaptable to different test configurations.

The part has been designed and implemented using CAD modelling and detailed fabrication drawings, integrating a set of assembled elements that ensure efficient operation in dynamic environments. It is made of stainless steel, which gives it high mechanical and thermal resistance, as well as ensuring good chemical compatibility with the captured waste.

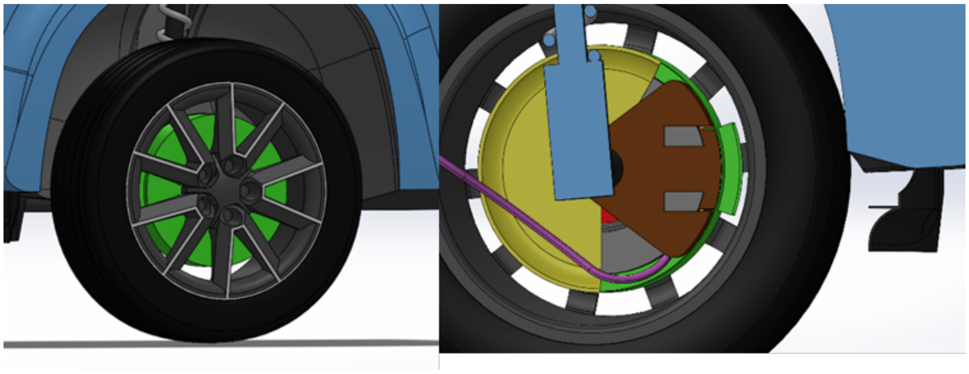

Figure 8 NEEVE Emissions Cover. Left, front view; right, rear view

Figure 8 shows a perspective view of the assembly mounted on a disc and brake pad. In the front view of the image, the cover (in green) and the wheel rim do not allow the internal components to be seen, these include:

- **The hub attachment core**, which ensures correct alignment of the system along with anchors to the yellow plate in the rear image,
- **The clamping plates** (one welded, one bolted), which allow for stable but removable mounting,
- **The inner baffles**, designed to channel the particle-laden airflow into collection areas,
- **And a nozzle on the violet probe**, strategically positioned to facilitate the suction of particulate material through the transfer line (transport and conditioning) to a filtering system or to external measurement and analysis (measurement section)

The shape of the device has been optimized to minimize turbulence, preserve the integrity and representativeness of the collected samples and allow its integration with aspiration or sensing systems. The wrap-around geometry, adjusted to the brake system dimensions, provides efficient coverage without interfering with disc or calliper operation. The device has been fluid-dynamically simulated under vehicle operating conditions including the geometry of the vehicle itself.

From the technical point of view, the assembly has been designed with tolerances that allow it to be manufactured using conventional processes, which facilitates its reproducibility and eventual scalability. Likewise, priority has been given to a structure that can be disassembled to facilitate both maintenance and inspection. The design does not change the original homologation of the vehicle.

At this stage of the project and given that part of the design could be subject to a future patent application, it has been decided to keep certain internal technical aspects confidential. Nevertheless, the device has been preliminarily validated at a functional level, and has been found suitable for emission tests under representative conditions.

This development is part of a broader strategy for the characterization and reduction of unregulated emissions, providing a valuable technical tool for research and technological development in the field of sustainable mobility.

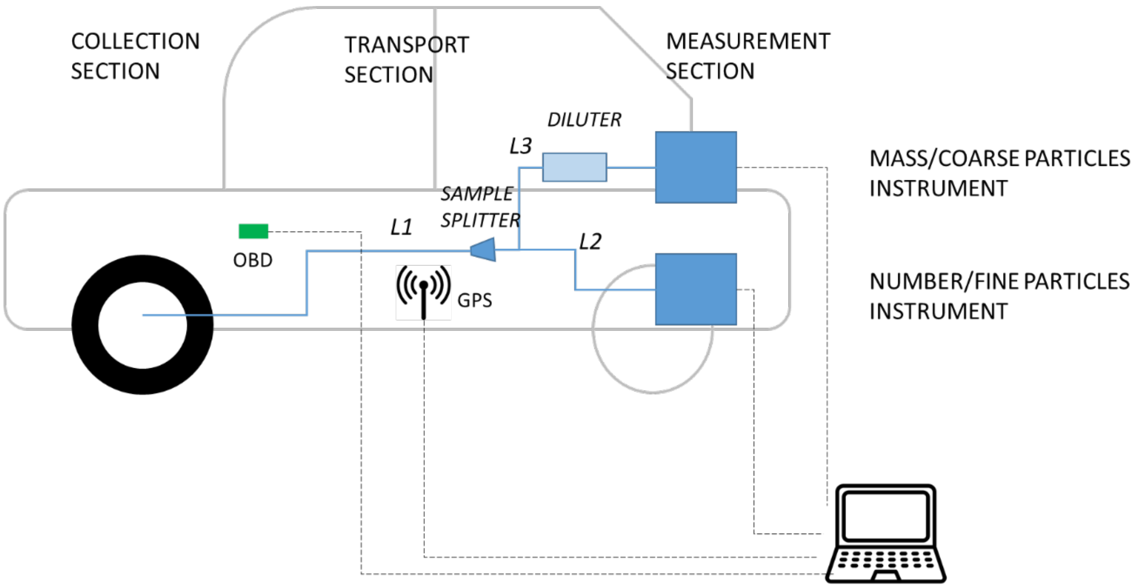

Figure 9 Schematic diagram of the initial prototype module

The transport section of the prototype module consists of three transfer lines (L1, L2 and L3) and one sample splitter. Optionally, one sample dilutor can be used. In the figure the sample dilutor is shown installed in the PM measuring instrument, because during the experiments realized it has been the used PM instrument the one which has been saturated. However, it could not be necessary if a different PM measuring instrument is used, or it could be installed in the PN measuring instrument instead. The sample splitter [Rodriguez, 2017] function is to divide the sample flow in two, keeping both subsamples representative of the emission. Transfer lines are made mainly of electrically conductive flexible polymer tubes, such as anti-static silicone, and metal fittings and tubes, where temperature precludes the use of polymers.

The measuring section of the first prototype module comprises two different instruments. One of them is intended to monitor PM1 (ultrafine and small fine particles) and the other one is intended for coarse particles. EEPS was used for PM1 and OPS was used for coarse particles. OBS-ONE were used for total PN.

Three of the instruments used are able to measure de PSD within their measuring size range, they directly measure number concentration. PM mass concentration can be calculated from the measurements, if the particles' density is known.

The determination of NEE PSD is interesting for research purposes. But it is also useful for selecting the lower size threshold for particle number concentration instruments.

The instruments used in the first prototype module are not necessarily the ones that will be used in the final prototype module. Research purposes have influenced greatly the selection of instruments. Once NEE are better known and characterised, other instruments can be used.

Besides real-time NEE data (concentration and PSD), other data is also recorded. The dynamometer test bench stores data regarding its operation. Data regarding operational parameters of the vehicle is collected and recorded using the OBD interface. During on-road tests, GPS receiver is used to continuously record position, altitude, speed, etc.

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8. References

Alemani, M., Nosko, O., Metinoz, I., and Olofsson, U., "A Study on Emission of Airborne Wear Particles from Car Brake Friction Pairs" *SAE Int. J. Mater. Manf.* 9(1):147-157, 2016,

https://doi.org/10.4271/2015-01-2665.

Al Wasif-Ruiz, T., Suárez-Bertoa, R., Sánchez-Martín, J.A., Barrios-Sánchez, C.C. (2025) "Direct measurement of brake wear particles from a light-duty vehicle under real-world driving conditions" *Environmental Science and Pollution Research* (2025) 32:2551-2560

https://doi.org/10.1007/s11356-024-35879-y

CEN, (2024) EN 16976:2024 Ambient air - Determination of the particle number concentration of atmospheric aerosol

Defra, (2019). “Non-Exhaust Emissions from Road Traffic” Air Quality Expert Group. Prepared for: Department for Environment, Food and Rural Affairs; Scottish Government; Welsh Government; and Department of the Environment in Northern Ireland

European Commission, (2017). Commission Regulation (EU) 2017/1154 of 7 June 2017 amending Regulation (EU) 2017/1151 supplementing Regulation (EC) No 715/2007 of the European Parliament and of the Council on type-approval of motor vehicles with respect to emissions from light passenger and commercial vehicles (Euro 5 and Euro 6) and on access to vehicle repair and maintenance information, amending Directive 2007/46/EC of the European Parliament and of the Council, Commission Regulation (EC) No 692/2008 and Commission Regulation (EU) No 1230/2012 and repealing Regulation (EC) No 692/2008 and Directive 2007/46/EC of the European Parliament and of the Council as regards real-driving emissions from light passenger and commercial vehicles (Euro 6)

European Commission, (2022). Proposal for a Regulation of the European Parliament and of the Council on type-approval of motor vehicles and engines and of systems, components and separate technical units intended for such vehicles, with respect to their emissions and battery durability (Euro 7) and repealing Regulations (EC) No 715/2007 and (EC) No 595/2009

European Commission, (2023). Commission Regulation (EU) 2023/443 of 8 February 2023 amending Regulation (EU) 2017/1151 as regards the emission type approval procedures for light passenger and commercial vehicles

European Parliament, (2007). REGULATION (EC) No 715/2007 of the European Parliament and of the Council on type approval of motor vehicles with respect to emissions from light passenger and commercial vehicles (euro 5 and euro 6) and on access to vehicle repair and maintenance information

Järvinen, A., Aitomaa, M., Rostedt, A., Keskinen, J., Yli-Ojanperä, J. (2014) “Calibration of the new electrical low pressure impactor (ELPI+)” *J. of Aerosol Sci.* 69:150-159

http://dx.doi.org/10.1016/j.jaerosci.2013.12.006

Johnson, T., Caldow, R., Pöcher, A., Mirme, A., et al. (2004). “A new electrical mobility particle sizer spectrometer for engine exhaust particle measurements” SAE Technical Paper 2004-01-1341

https://doi.org/10.4271/2004-01-1341

Knutson, E.O. and Whitby, K.T. (1975). “Aerosol Classification by electric mobility: Apparatus, theory, an applications” *J. Aerosol Sci.* 6:443-451 https://doi.org/10.1016/0021-8502(75)90060-9

Ligterink, N.E., van Mensch, P., Cuelenaere, R.F.A. (2016) "NEDC - WLTP comparative testing" TNO report TNO 2016 R11285

Liu, X, Zhao, F., Hao, H., Chen, K., Liu, Z., Babiker, Amer, A.A. (2020) "From NEDC to WLTP: Effect on the Energy Consumption, NEV Credits, and Subsidies Policies of PHEV in the Chinese Market" *Sustainability* 2020, 12, 5747.

doi:10.3390/su12145747

Marple, V.A. (2004) "History of Impactors—The First 110 Years" *Aerosol Science and Technology* 38:247-292

https://doi.org/10.1080/02786820490424347

Piscitello, A., Bianco, C., Casasso, A., Sethi, R. (2021). "Non-exhaust traffic emissions: Sources, characterization, and mitigation measures" *Science of the Total Environment* 766 (2021) 144440

https://doi.org/10.1016/j.scitotenv.2020.144440

Rodriguez, J.J., Rojas, E., Sanz, D., Martínez, J.I., Archilla, V., González, D., González, A., Aragón, G. (2017). "Diseño de splitters de flujo variable para estaciones de muestreo de PM. Aplicación en el Centro de Ensayos de Turborreactores (INTA)" Informes Técnicos Ciemat 1399. CIEMAT Ed.

ISSN: 1135-9420 NIPO: 058-17-006-2

Tammet, H., Mirme, A., Tamm,E.(2002). "Electrical aerosol spectrometer of Tartu University" *Atmospheric Research*, 62(3–4): 315–324.

https://doi.org/10.1016/S0169-8095(02)00017-0

UN, (2019). Addendum 153 – UN Regulation No. 154. Uniform provisions concerning the approval of light duty passenger and commercial vehicles with regards to criteria emissions, emissions of carbon dioxide and fuel consumption and/or the measurement of electric energy consumption and electric range (WLTP)

https://unece.org/transport/documents/2021/02/standards/un-regulation-no-154-worldwide-harmonized-light-vehicles-test

UNECE, (2014). Global technical regulation No. 15 Worldwide harmonized Light vehicles Test Procedure

UNECE, (2023). UN Global Technical Regulation No. 24 Laboratory Measurement of Brake Emissions for Light-Duty Vehicles

WHO, (2021) “Global air quality guidelines: particulate matter (PM2. 5 and PM10), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide” Geneva: World Health Organization; 2021.

https://www.who.int/publications/i/item/9789240034228

Xu, R. (2015) “Light scattering: A review of particle characterization applications” *Particuology* 18:11-21

http://dx.doi.org/10.1016/j.partic.2014.05.002

Zardini, A. and Bonnel, P. (2020) “Real Driving Emissions Regulation: European Methodology to fine tune the EU Real Driving Emissions data evaluation method” EUR 30123 EN, Publications Office of the European Union, Luxembourg, 2020, ISBN 978-92-76-17157-7, doi:10.2760/176284, JRC119889.