Ref. Ares(2023)7901696 - 20/11/2023

LENS L-vehicles Emissions and Noise mitigation Solutions

D3.1
Method and systems for on-board measurement of pollutants emissions

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101056777

Deliverable No.	D3.1	
Deliverable title	Method and systems for on-board measurement of pollutants emissions	
Deliverable type	Report	
Dissemination level	PU - Public	
Deliverable leader	TU Graz	
Contractual due date	31.10.2023	
Actual submission date	20.11.2023	
Version	1.0	
Written by	Sebastian Schurl, Stephan Schmidt (TU Graz), Michal Vojtisek (CZU), Philippe Degeilh (IFPen), Giorgos Triantafyllopoulos, Leonidas Ntziachristos (EMISIA)	10.11.2023
Reviewed by	Åke Sjödin (IVL), Frank Schwarz (BMW)	18.10.2023
Approved by	All partners	17.11.2023

Disclaimer

Revisions table

Version	Date	Change
1.0	20.11.2023	First submission to the EC

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101056777

Table of contents

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101056777

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101056777

Executive summary

This report presents an in-depth exploration of methods and systems for on-board measurement of pollutant emissions in the context of Real Driving Emissions (RDE) testing. The study encompasses several critical areas, including vehicle setup and preparation for real drive measurements, the requirements for RDE trips across various L-vehicle subcategories (e.g., mopeds, motorcycles), metadata, measurement data, data storage, and an examination of the measurement devices used within the consortium.

Vehicle Setup and Preparation for Real Driving Measurements:
The report commences by elucidating the essential procedures and considerations for preparing vehicles for real-world emissions measurements. It covers the necessary instrumentation, calibration, and maintenance requirements for accurately assessing pollutant emissions under diverse driving conditions.

RDE Trip Requirements for Different L-vehicle Subcategories:
To ensure comprehensive coverage, the study defines the specific RDE trip requirements for a spectrum of L-vehicle subcategories, including mopeds, motorcycles, other subcategories.

Requirements for Metadata, Measurement Data, and Data Storage:
The report emphasizes the importance of metadata and detailed measurement data in supporting the accuracy and reliability of emission assessments. It outlines the mandatory parameters and data for capturing crucial information during the testing process and provides compatibility with the data storage solution LENSDB, enabling traceability and data integrity.

Measurement Devices for On-Road Testing:
The final chapter delves into an exhaustive analysis of the measurement devices employed within the consortium. This includes a comprehensive overview of commercially available Portable Emissions Measurement Systems (PEMS), mobile Fourier Transform Infrared Spectroscopy (FTIR) devices, and research Smart Emission Measurement Sensors (SEMS). The discussion extends to additional equipment, such as On-Board Diagnostics (OBD), Controller Area Network (CAN) interfaces, and Global Positioning System (GPS) data integration, all of which play a vital role in the accurate measurement and analysis of pollutant emissions under Real Driving conditions and enable calculations for WP6.

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101056777

List of abbreviations

#/s	Particulates per Second
CAN	Controller Area Network
CLD	Chemiluminescence Detector
CO	Carbon monoxide
CO_2	Carbon dioxide
CPC	Condensation Particle Counter
CVS	Constant Volume Sampling System
ECU	Engine Control Unit
EFM	Exhaust Flow Meter
FMEP	Friction Mean Effective Pressure
FTIR	Fourier Transform Infrared Spectroscopy
g/s	Grams/Second
GPS	Global Positioning System
HEPA	High Efficient Particulate Air Filter
LDV	Light Duty Vehicle
LENSDB	LENS Database
NDIR	Non-Dispersive Infrared Detector
NH_3	Ammonia
NO	Nitrogen oxide
NO_2	Nitrogen dioxide
NOx	Nitrogen oxides
OBD	Onboard Diagnosis
PAS	Photoacoustic Sensor
PEMS	Portable Emission Measurement System
PN	Particulate Number Emission
ppm	Parts Per Million
PTFM	Pitot Flow Meter
RDE	Real Drive Emissions
RPM	Revolutions Per Minute
SEMS	Smart Emission Measurement Sensors

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101056777

List of figures

List of tables

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101056777

1. Measurement Workflow

1.1 Workflow

The workflow of the on-road measurement procedure is shown in Figure 1-1.

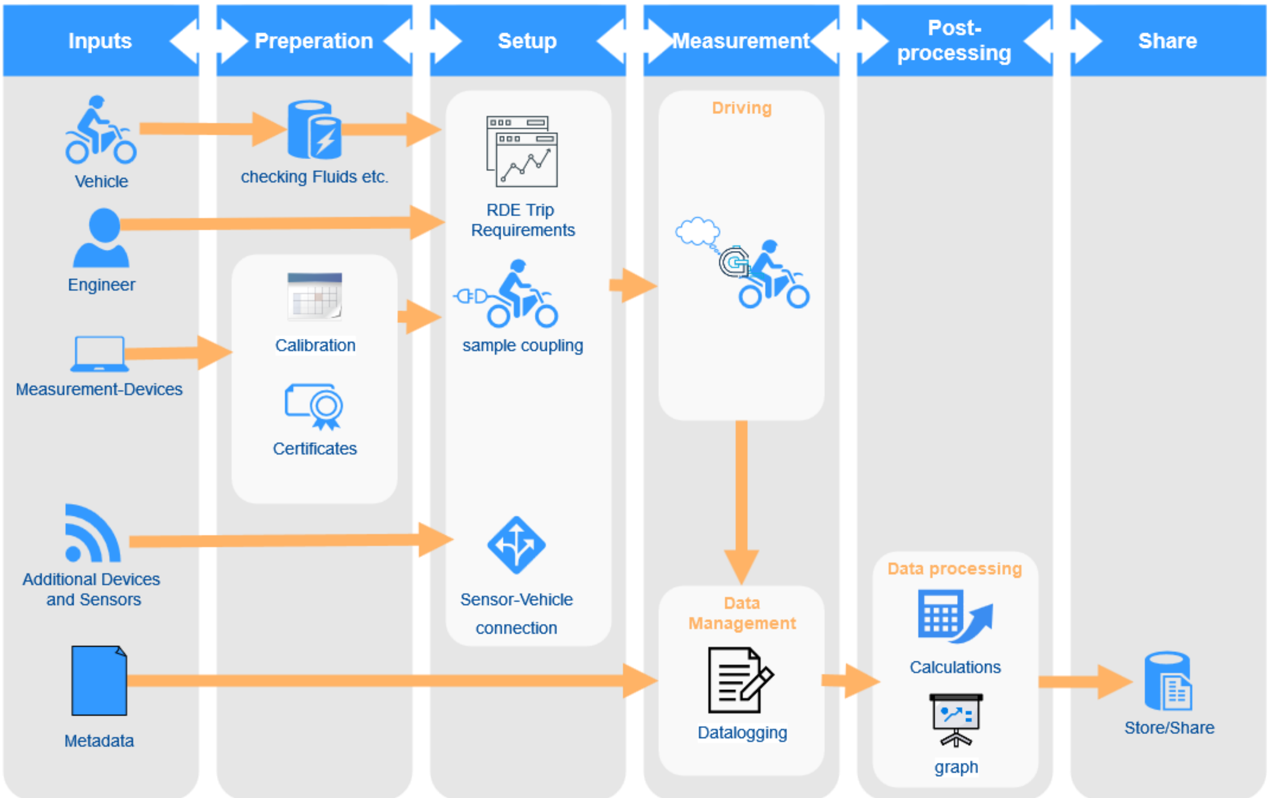


Figure 1-1: Workflow of the RDE on-road measurement procedure

1.2 Suitability of measurement systems for various categories of L-Cat vehicles

Special care has to be taken regarding the use of measurement equipment on L-category vehicles. The described exhaust gas measurement devices and platforms (see chapter 6 Measurement Devices for On-Road Testing) cause a considerable additional mass and packaging volume, which must be mounted on the vehicle.

1.2.1 Exhaust Gas Mass Flow Measurement

The most difficult measurement value is the exhaust gas mass flow. Due to specific conditions of L-category vehicle propulsions, the adoption of passenger car and Light / Heavy Duty vehicle measurement equipment is not possible in all cases. Main reason is the combination of low cylinder number together with short exhaust system length and low volume. This leads to strong pulsations and back-flow of the exhaust gas

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101056777

mass flow, which makes a standard measurement with the pitot principle not reliable. Especially for single cylinder and low-capacity engines this measurement method cannot be applied.

Alternative measurement approaches are calculations based on transient engine variables like engine speed, engine load, intake manifold pressure and lambda. These data can be gathered from OBD for all vehicles EU4 and later.

Another approach is using transient injection mass together with Lambda sensor data. This requires additional measurement equipment or access to the engines can-bus data.

Last approach is the measurement of concentrations in real-world driving followed by a measurement run on the chassis dyno with CVS emission measurement using the RDE route data (speed and slope) and comparing the concentrations from real-world driving.

1.2.2 PEMS Systems

A typical PEMS system comprise various analysers for measuring emission concentrations and an Exhaust Flow Meter (EFM) for measuring exhaust mass flow and has a mass of approximately 50+ kg including the battery capacity for 1-2h operation time. This mass and packaging volume will influence the vehicle driving characteristics, dependent on the percentage of this additional mass to the vehicle mass. The smaller and lighter a vehicle is, the bigger the influence. Additionally, a mounting of the PEMS system on smaller vehicles is difficult to not manageable, depending on the size and type (scooter, naked, racing, …) of the vehicle. Prior investigations showed that 2-wheeler in the class of L1e-B cannot be equipped with a PEMS, L3e-A1 (125cc class) might be equipped with major influences. For 2-wheeler L3e-A2 and L3e-A3 a mounting is possible in most cases, whereas the mounting situation of some scooters may render the use of PEMS impossible.

1.2.3 SEMS Systems

SEMS systems are based on sensors instead of analysers; this leads to considerable smaller packaging size and lower mass. Not in all cases an exhaust gas mass flow measurement is provided with a SEMS. SEMS might suit for smaller 2-wheeler categories, whereas the installation possibility of pitot type exhaust gas mass flow measurement systems on small capacity, single-cylinder systems is difficult, and the accuracy is not within a reasonable limit. To get exhaust gas mass flow data, several procedures as described above are possible.

For L1e and some L3e-A1 vehicles the following procedure is suggested:

1. RDE trip measurement with SEMS with or without EFM including GPS and RPM logging.
2. If possible, on-road coast down with SEMS mounted for derivation of chassis dyno road load factors.
3. Simulation of RDE trip on chassis dynamometer with on-road load parameters, using the logged speed and inclination trace from the RDE trip. Using standard lab-test equipment like CVS and emission analysers this delivers emissions in g/s. The logged emission concentration trace [ppm] of the SEMS without EFM can be used to compare the on-road emission trace with the lab-test emission concentration trace, to ensure a good compliance of on-road and lab-test.

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101056777

2. Measurement Procedure

The RDE measurement should follow the procedure in chapter "Vehicle setup and preparation".

1. All vehicles except L1e and some L3e-A1 should be measured according to "chapter RDE Trip Requirements". The decision is based on the neglectable influence of the PEMS measurement equipment on the driving characteristic of the specific vehicle as well as on the possibility of measurement equipment mounting on the vehicle. This must be decided and noted in the measurement report by the conducting organisation for each single vehicle separately.
2. For L1e and some L3e-A1, where a not neglectable influence of the PEMS measurement equipment on the driving characteristic of the specific vehicle is anticipated and the possibility of measurement equipment mounting on the vehicle is not given, RDE trip measurement with SEMS with or without EFM including GPS and RPM logging is recommended. In the case of manual transmission, a gear shift logging is desired.
3. Decision for EFM measurement principle and setup should be made according to Figure 2-1.
    a. Use of standard EFM based on Pitot principle.
    b. Calculation of exhaust gas mass flow out of OBD data based on engine load (see Formula 1 and Formula 2: 4-stroke engine and Lambda = 1).

$$\mathrm{Volume}Flow_{Air} = Engine_{Load} \cdot Engine_{Capacity} \cdot \frac{Engine_{Speed}}{2} \cdot \frac{Baro}{29{,}92} \cdot \sqrt{\frac{298}{T_{intakeAir} + 273}} \qquad \textit{Formula 1}$$

$$\mathrm{VolumeFlow_{Exhaust}} = VolumeFlow_{Air} \cdot \left(1 + \frac{1}{14{,}7}\right) \qquad \textit{Formula 2}$$

    c. Calculation of exhaust gas mass flow out of CAN-Bus data based on injection mass and lambda.

    To calculate the exhaust mass flow rate from lambda λ and injection volume flow Q_{inj}, first the air-to-fuel ratio AFR of the engine using the lambda value must be determined. The stoichiometric AFR is different for different fuels, for example, for gasoline it is typically around 14.7:1. For calculating the mass flow rate of air entering the engine using the injection volume flow Q_{inj} and the density of fuel ρ_{fuel} . The mass flow rate of air can be calculated acc. Formula 3. By having the calculated air mass flow and the AFR, the mass flow rate of fuel can be calculated acc. Formula 4. By using the equation of continuity, the total exhaust mass flow rate can be summed by adding together the mass flow rates of air and fuel entering the engine acc. Formula 5 [1].

$$MassFlow_{Air} = AFR \cdot Q_{inj} \cdot \rho_{fuel} \qquad \textit{Formula 3}$$

[1] Note that these calculations assume that all the fuel injected into the engine is completely burned, which may not always be the case in practice. Additionally, the density of fuel and the AFR may vary depending on operating conditions and other factors, so these values may need to be measured or estimated accurately for reliable results.

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101056777

$$MassFlow_{Fuel} = \frac{MassFlow_{Air}}{AFR} = Q_{inj} \cdot \rho_{fuel}$$ *Formula 4*

$$MassFlow_{exh} = MassFlow_{Fuel} + MassFlow_{Air}$$ *Formula 5*

d. Measurement of exhaust gas mass flow on chassis dyno using real-world route data and real-world trip tail pipe emission concentration trace for comparison. Simulation of RDE trip on chassis dynamometer with on-road load parameters (if available), using the logged speed and inclination trace from the RDE trip as well as gear shift indications (if available). Using standard lab-test equipment like CVS and emission analysers this delivers emission in g/s and ppm. The logged emission concentration trace [ppm] of at least one exhaust gas emission component of the SEMS without EFM can be used to compare the on-road emission concentration trace with the lab-test emission concentration trace, to ensure a good compliance of on-road and lab-test.

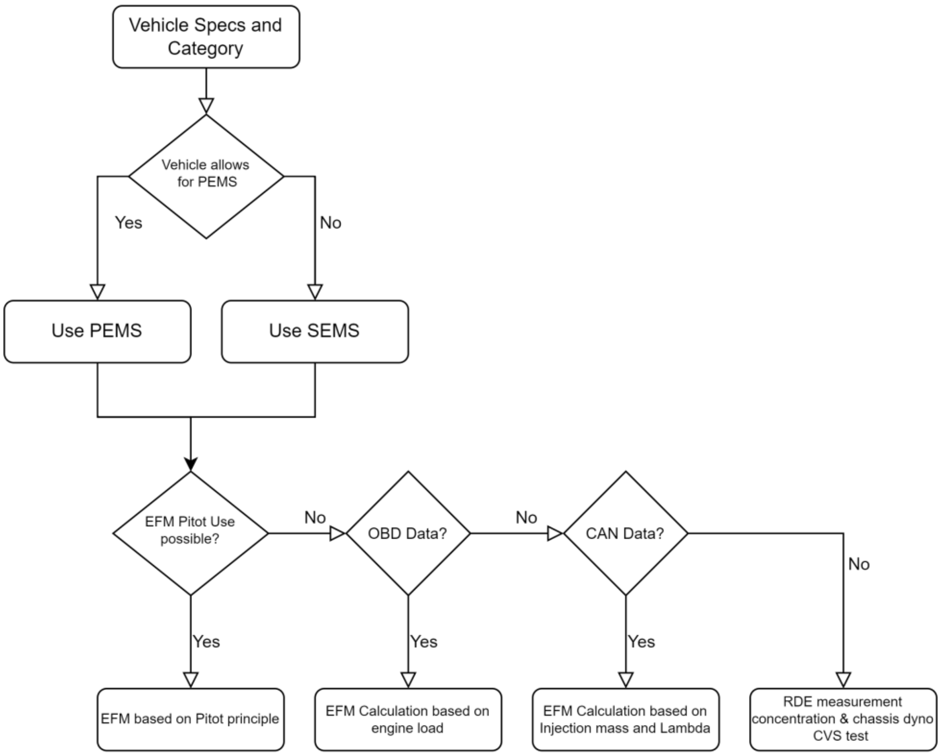


Figure 2-1: EFM Measurement decision schemata

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101056777

3 Vehicle setup and preparation

3.1 Test vehicle preconditioning

Test vehicle preconditioning is not required.

3.2 Fluids Check

Before conducting any measurement test, it is imperative to check the condition of the vehicle's fluids. This includes engine oil, coolant, and transmission fluid, among others. Proper fluid levels and quality are crucial, as they can directly impact vehicle performance and emissions. Any deviations from standard conditions should be documented, as calculation results will be based on these parameters.

3.3 Fuel Properties Documentation

Fuel properties play a significant role in emission testing, as they can affect the combustion process and emission characteristics. Detailed documentation of fuel properties, including fuel type, density, octane rating, C:H:O-share, information about lubrication (i.e. fuel / oil mixture, external loss lubrication), is essential for accurate analysis and comparison of test results. Inconsistent fuel properties can lead to variations in emissions data.

3.4 Battery Status Check

For smaller motorcycles and electric vehicles, battery status is a critical consideration. A fully charged and healthy battery is essential to avoid any interruptions or alterations in emissions data caused by recharging during the test. Ensuring a stable power supply for all vehicle systems is mandatory.

3.5 Coupling of EFM to the vehicles tail pipe

The coupling of the heated EFM intake pipe to the vehicle tail pipe is done by using a cone, fitting properly into the tail pipe. This cone has to have a narrow angle to ensure a tight fit. For each tail pipe diameter range of X +/-1mm a separate cone has to be manufactured to prevent flow restrictions in the tail pipe caused by the cone (see example in y / twin tail pipe configuration Figure 3-1).

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101056777

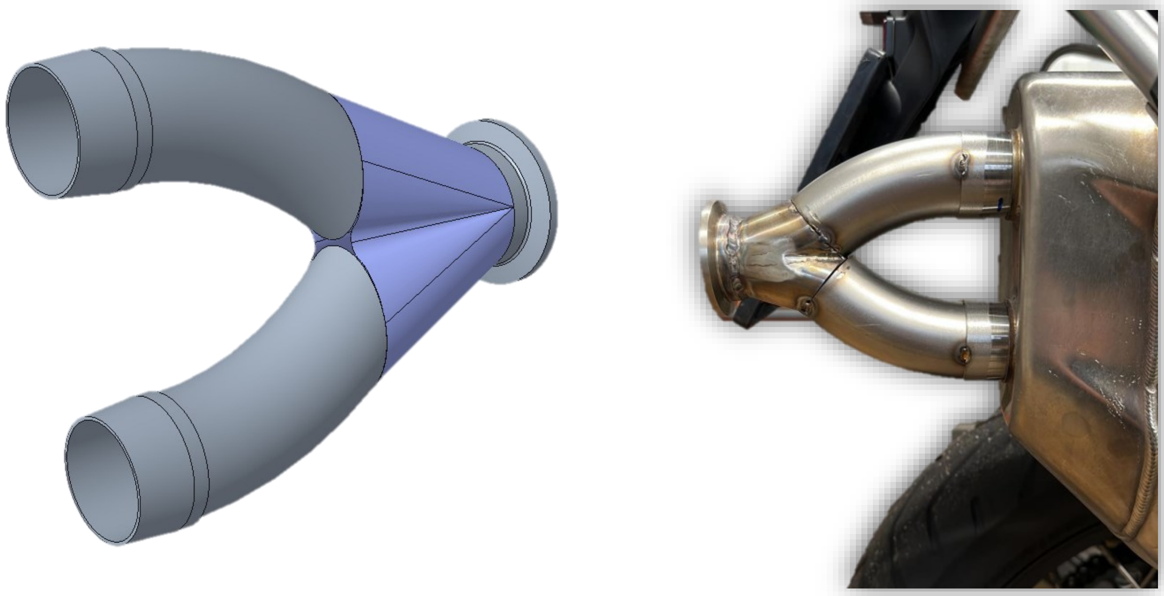


Figure 3-1: Example of cone fitting for exhaust gas flow measurement device and tail pipe connection in a double tail pipe configuration

3.6 Coupling SEMS tail pipe exhaust gas sampling

The tail pipe exhaust gas sampling in case of “no EFM used” can be done by a plug-in sampling probe, whereas special care has to be taken for influence of secondary air intake from the tail pipe. A calculation of the exhaust gas mass flow has to be performed using alternative methods. If this is not possible, a verification measurement in lab has to be performed.

Figure 3-2: Plug-in exhaust gas tail pipe probe

3.7 Additional measurement channels, devices, and sensors

All additional equipment has to be logged either in the PEMS / SEMS system or externally, whereas with external logging a time alignment has to be performed in the postprocessing.

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101056777

4 RDE Trip Requirements

Real Driving Emissions (RDE) testing in Project LENS is designed to capture a wide range of real-world driving scenarios, ensuring that emissions data accurately represent typical driving patterns for each subcategory of L-vehicles. The RDE trip requirements consider the unique characteristics of different L-vehicle subcategories and are subject to be updated in details after first measurements from all sub-categories have been performed. Two major trip categories are defined. First, the “Standard RDE” trip capturing the standard real-world driving scenarios and second, the “Extreme RDE” capturing the potentially high emission events according to Deliverable D6.1.

4.1 Standard RDE Trip

The standard RDE trip definition is based on trip time in different areas, namely urban, rural and highway. Differentiation between urban, rural and highway is done by geographic boundaries, not speed limit definition. All trip definitions are guidelines to be followed as good as possible according to best engineering practises. The main purpose is to reflect the real driving situations of the vehicle category. Stand-still time should be monitored. If stand-still time is excessive (>30% urban trip time) these trip segments should not be considered and a cold start at the beginning is required.

4.1.1 50cc Mopeds (L1e-B)

For 50cc mopeds belonging to the L1e-B subcategory, it is recommended to focus primarily on urban driving conditions. These vehicles are typically used for short-distance urban commuting, and thus, the RDE tests should reflect this usage pattern. Minimum trip time should be 20min.

4.1.2 Larger Capacities (larger than 50cc)

For larger capacity L-vehicles, which include scooters, motorcycles, sportbikes, and cruisers, a balanced approach to RDE testing is suggested. It is recommended to have a roughly equal distribution of driving scenarios, with approximately one-third of the testing focused on urban, one-third on rural, and one-third on highway driving conditions. Minimum trip time should be 30min.

4.1.3 Sportbikes and Cruisers

In the case of sportbikes and cruisers, the share of rural and highway driving conditions can be adjusted to reflect their typical usage patterns. These types of motorcycles are often associated with longer-distance and recreational riding, so it is acceptable to have a greater emphasis on rural and highway scenarios. Minimum trip time should be 30min.

4.2 Extreme RDE Trip

To ensure comprehensive testing and to account for extreme situations that may affect emissions, LENS incorporates these scenarios into testing protocols. However, it is essential to clearly document these extreme conditions in the test data and provide detailed explanations in the LENSDB. This documentation ensures transparency and allows for a thorough understanding of any deviations from standard test

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101056777

scenarios. Extreme RDE trips should be compiled out of the Table 4-1[2]. A sequential run of the various test conditions is recommended, ideally with a repetition of each test condition 2-3 times.

A possible sequence would be: Cold start followed by 2-3 times RPM burst (condition 2), then 2-3 times Acceleration from stand still (condition 3) and so on until condition 9. The test conditions should be ordered in a sequence to ensure 1.) safe driving 2.) no engine damage (mandatory engine warm up), and 3.) practicability.

For the extreme RDE trip an appropriate route must be defined and all conditions must be adapted to the capability of the vehicle and boundary conditions like speed limit, increased mass, and lowered manoeuvrability of the vehicle.

Table 4-1: Recommended driving conditions for the tail pipe emissions program, ordered in possible test sequence form Table 4.2 of LENS Deliverable 6.1

Condition	Vehicle operation	Short name	Already in emission TA?	Remarks
(1) Cold start (mainly for emissions)	Engine start	'coldstart'	Yes	Emission budget?
(2) rpm burst (revving)	Stationary, short activation and release of accelerator	'rpmburst'	No	From idling, 3x 50% max rpm
(3) Acceleration from standstill, G1, G2 Loaded + unloaded	Acceleration, late gear change	'rpmlongacc'	Partly	
(4) Max rpm; esp. mopeds, scooters, sports MCs	Constant speed with max rpm	'rpmconthi'	No	Mopeds: Wide Open Throttle
(5) Transition from constant speed or acceleration phases to deceleration phases	Deceleration	'rpmdropoff'	Partly	
(6) 'Max' acceleration from standstill, G1, G2	Acceleration	'rpmshortacc'	No	Sportive and dynamic driving
(7) (Strong) Acceleration at speed, from 50 to 100 km/h	Acceleration, may be varied	'rpmmidspeedacc'	No	
(8) rpm fluctuation	Variable speed	'rpmfluct'	No	Accelerator intermittent – dynamic driving
(9) Backfire (occurrence, distance not critical)	Multiple gear changing or manual operation	'bang'	No	Condition at which backfire would be most likely

[2] Table 4.2 "Recommended driving conditions for the tail pipe emissions program, ordered in possible test sequence" from Deliverable 6.1 "Real world driving conditions and requirements for the LENS test program".

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101056777

4.3 Conclusion

Measurement types in Project LENS encompass both lab and on-road assessments, ensuring a thorough examination of vehicle emission characteristics. The use of CVS systems, standardized measurement devices, test cycles, and rigorous adherence to regulations guarantee data accuracy and reliability. The integration of PEMS and SEMS platforms for on-road testing further enhances the project's capability to collect high-quality emissions' data, contributing to a comprehensive understanding of vehicle emissions' performance. By tailoring the RDE trip requirements to the specific characteristics of each L-vehicle subcategory, Project LENS aims to collect emissions data that are not only representative but also reflective of real-world usage patterns. This approach provides valuable insights into emissions' performance across different L-category vehicle subcategories and helps to develop a more accurate understanding of their environmental impact.

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101056777

5 Required Data and Data Storage

For the data analysis of on-road measurements, several data types are necessary. All data must be prepared and delivered in a structured order and will be inserted in a special data base, the LENSDB. This data base allows for access of the consortium members for later use during the research program as well as for further use after the research program. All necessary data are explained in the LENSDB data template excel sheet. In the following, the data types are explained.

5.1 Meta data: Vehicle specification and test conditions

Several meta data from the vehicle and test conditions are necessary. This comprises, amongst others, vehicle type, category, subcategory and specifications, mileage and status of vehicles and test conditions like driving style, weather and so on.

5.2 Measurement data

The measurement data itself comprises time resolved emission data, if possible, exhaust mass flow data, and other time resolved information:

- Engine RPM: Engine revolutions per minute by using OBD data, CAN bus or pickup signal.
- OBD Data for EU4[3] and EU5[3] vehicles: PID04 (calculated engine load), PID0B (intake manifold absolute pressure), PID 0C (engine speed), PID 0D (vehicle speed), PID 0F (intake air temperature) ,… according to J1979 SAE standard.
- GPS Data: Including vehicle speed and altitude.
- Emission Data: Emissions should be reported in grams per second (g/s) or counts per second (#/s).
- Exhaust flow mass [g/s].

[3] For EU4 and EU5 L-Cat vehicles OBD data provision is regulated in Type Approval Regulations EU168/2013 Annex IV 1.8.2

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101056777

6 Measurement Devices for On-Road Testing

Two different measurement system types are available within the consortium for on-road emissions measurements. Commercially available Portable Emission Measurement Systems (PEMS) and Smart Emission Measurement Systems (SEMS).

6.1 Portable Emissions Measurement Systems (PEMS)

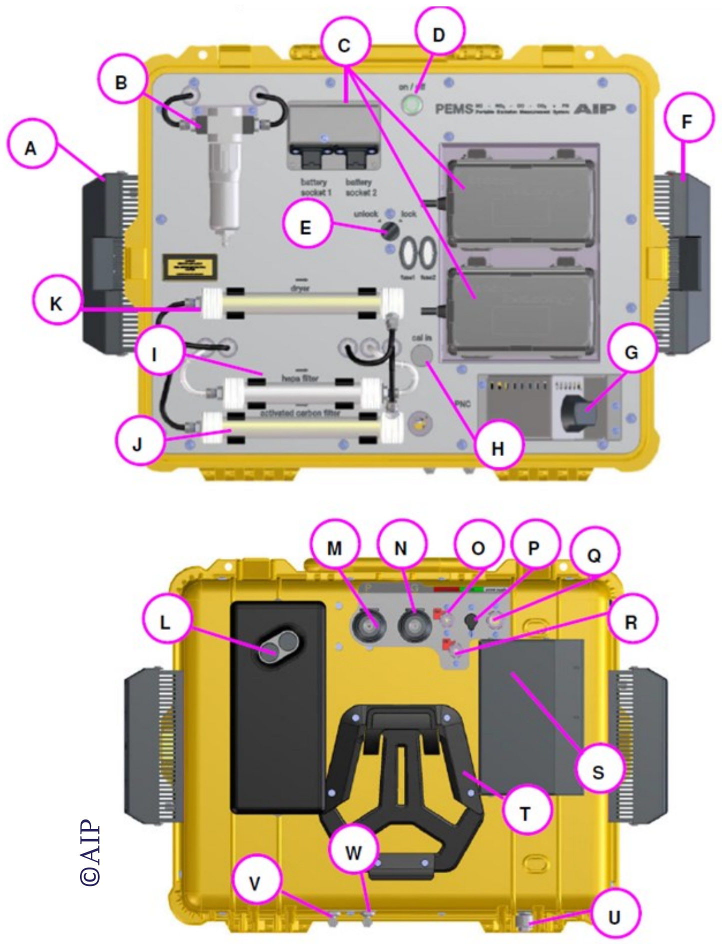
PEMS, similar to those used in passenger car testing, comprise various analysers for measuring emission concentrations and an Exhaust Flow Meter (EFM) for measuring exhaust mass flow. PEMS enable the calculation of gaseous emissions in the intended units. As an example, the PEMS system from AIP[4] is explained in the following.

6.1.1 AIP PEMS

The AIP PEMS (Figure 6-1) is used to determine the gaseous emission components CO, CO_2, NO_x (NO + NO_2) and the particle number concentration PN on motor vehicles in real vehicles in real driving conditions. The measuring device operates in compliance with the EU RDE-LDV legislation (EU Regulation 2017/1151). The analysis is integrated into a robust, waterproof housing (IP57) with passive cooling and is operated self-sufficient with Li-Ion batteries. During the design phase, attention was paid to a light-weight construction and a simple installation at the rear of the vehicle. The carrier is conveniently attached to the trailer coupling with a clamping lever. The measuring case can then be fixed to the carrier by means of a click system. The gaseous pollutants are detected by means of non-dispersive infrared sensors (CO and CO_2), chemiluminescence detector (NO) and photoacoustic sensor (NO_2). For particle number determination, particles with an electrical mobility diameter of 10 nm to about 2.5 µm are measured. The measuring system has been developed in accordance with the PMP protocol, which is the basis of the current legislation for the determination of the particle number concentration on the exhaust roller dynamometer. The system consists of a first dilution stage (PND1), a catalytic stripper, a second dilution stage (PND2) and a condensation particle counter (CPC). The 50 % counting efficiency of the mobile CPC is 10 nm. Sampling is carried out by means of a heated sampling line out of the exhaust flow meter (EFM) which calculates the exhaust flow based on pressure measurements (Pitot).

[4] https://www.aip-automotive.de/en/

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101056777



A: cooler
B: dehumidifier and filter
C: battery
D: power button
E: locking system
F: cooler
G: CPC
H: calibration inlet
I: HEPA filter
J: active carbon filter
K: dryer
L: dilution
M: heated sampling line inlet PN
N: heated sampling line inlet gas
O: supply of heated sampling line gas
P: supply EFM
Q: power supply
R: supply of heated sampling line PN
S: gas cooler
T: mounting system
U: purge air
V: exhaust condensate
W: exhaust gas

Figure 6-1: AIP PEMS

Analyzers:

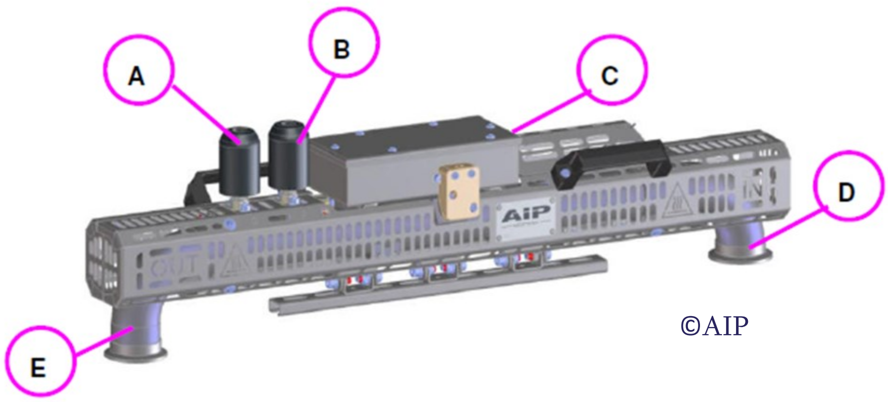
- CLD for measuring NO
- PAS for measuring NO_2
- NDIR for measuring CO/CO_2

Table 6-1: Characteristics of AIP PEMS analyzers

	CO	CO_2	NO	NO_2
Principle	NDIR	NDIR	CLD	PAS
Range	0 – 5 Vol.-%	0 – 20 Vol-%	0 – 2500 ppm	0 – 1000 ppm
Precision	< 0,3 % o.E.	< 0,3 % o.E.	< 1 % o.E.	< 0,5 % o.E.
Noise	< 0,3 % o.E.	< 0,2 % o.E.	< 0,4 % o.E.	< 0,06 % o.E.
Zero-drift	≤ 20 ppm	≤ 500 ppm	≤ 0,5 ppm	≤ 0,5 ppm
Span-drift	≤ 2 % o.M. or ≤ 20 ppm	≤ 2 % o.M. or ≤ 500 ppm	≤ 2 % o.M. or ≤ 5 ppm	≤ 2 % o.M. or ≤ 5 ppm
Accuracy	±2 % o.M. oder ±0,3 % o.E.			

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101056777

6.1.2 AIP EFM



A: sampling line gas I **B**: sampling line PN I **C**: supply and data connector I **D**: exhaust inlet I **E**: exhaust outlet

Figure 6-2: Exhaust gas flow meter AIP

The AIP Exhaust Flow Meter (EFM) (Figure 6-2) determines the exhaust gas mass flow in compliance with EU RDE-LDV Legislation (Regulation (EU) 2017/1151). The direct determination of the exhaust gas mass flow at the tailpipe, together with sampling and the determination of the gas concentrations and the number of particles through a PEMS system provides the most accurate method for determining mass emissions. The AIP EFM works according to the proven Pitot principle for determining flow rates robust differential pressure measurement. High-resolution differential pressure sensors arranged in a cascade are used to measure differential pressure used. The sampling and evaluation are done up to 5 kHz. The gas density is determined by measuring pressure and temperature in the measuring section.

6.1.3 Additional equipment

- T + Rh Sensor: for measure ambient conditions.
- GPS module: for delivering accurate GPS data including vehicle speed and altitude.
- CAN Interface: for read out ECU data like engine speed and others.

6.1.4 Assessment regarding Benefit and Disadvantage

+ High accuracy.
+ Exhaust mass flow can be measured.
- Exhaust mass flow measurement high in-accuracy due to pressure pulsations. Lower accuracy for single cylinder, short exhaust pipe and at low mass flow.
- High weight, big packaging volume → suitable only for 2-wheeler vehicles with cc >=125, mounting on scooter difficult.
- Exhaust flow measurement needs a connection between exhaust muffler and EFM device which can be difficult to establish.

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101056777

6.2 Smart Emission Measurement Systems (SEMS)

SEMS are provided by consortium partners Horiba (for NO_x) TUG (for PN) and EMISIA (for CO, CO_2, NO and Black Carbon Particle Number). To ensure the usability of SEMS data, SEMS can be combined with an EFM or other devices to measure or estimate exhaust mass flow and enable emission calculations in the intended units.
The integration of both PEMS and SEMS platforms allows for comprehensive on-road emissions measurement, covering a wide range of pollutants and providing valuable insights into real-world emissions behaviour.

6.2.1 HORIBA SEMS

The HORIBA SEMS (Figure 6-3) allows measurement of NO_x in real driving conditions. In a first cavity, a ceramic sensor element made of zirconium electrolyte measures the oxygen concentration entering from the exhaust gas through a diffusion barrier. Measurement is done by pumping oxygen ions through the yttrium-stabilized zirconium which becomes porous for oxygen ions around 600°C, and by measuring the established current. The oxygen concentration inside the cavity is controlled to a constant concentration around 10. Other components of the exhaust gas like HC, CO and H_2 are oxidized at the pumping electrode in the first cavity. NO_2 in the exhaust gas is reduced to NO and the released oxygen is pumped out of the cell. From the first cavity the test gas with the remaining few ppm O_2 and the NO enters a second cavity, where any gaseous oxygen is totally removed by an auxiliary ion pump. At the measuring electrode NO is converted to N_2 + O_2 and the oxygen generated by the reduction of NO is pumped out of the cell. The amperometric measurement of the generated oxygen represents the NO_x concentration of the exhaust gas. An electronic control unit (ECU) provides power control for heating the sensor element to operating temperature. The ECU provides the measured gas concentrations digitally via CAN bus to a datalogger which captures GPS and weather station data.

The requirement of oxygen in the exhaust gas to enable proper functioning of the sensor makes zirconia-electrolyte based sensors appropriate for diesel and lean burn conditions. Category L vehicles are dominantly running on gasoline engines generating mostly oxygen free exhaust gas. This requires the introduction of additional oxygen into the measured exhaust gas. As the O_2 concentration needs to be only a few tens ppm, only a small amount of ambient air is pumped into the exhaust gas stream upstream of the zirconia sensor. An NH_3 filter is further upstream of the mixing point to remove the interfering component and to reduce pressure surges from the exhaust, similar to a buffer tank. An NO_x span gas can be provided at the exhaust gas inlet to determine the dilution ratio of the setup.

At the time of this report, the SEMS was tested in its laboratory setup with a deviation below 10 % to a direct raw analyser for 2 different types of motorbikes. Testing at TU Graz showed an underestimation by 20 %. However, after shipping several issues were detected which could not be completely solved. A second version has been prepared at HORIBA and is under evaluation.

The analyser is integrated into a robust housing and can be operated with LiFePo4 batteries for approximately 2.5 hours. Installation on the vehicle can be done by using straps for dedicated attachment points. The integration of a Pitot tube and the required electronics are also under preparation.

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101056777

Table 6-2: Characteristics of HORIBA SEMS

	NO_x
Principle	Electro. chem
Range	0 – 1650 ppm
Accuracy*	± 10 ppm at low conc.
Interferences	NH_3
Warm up time	< 1 Minute

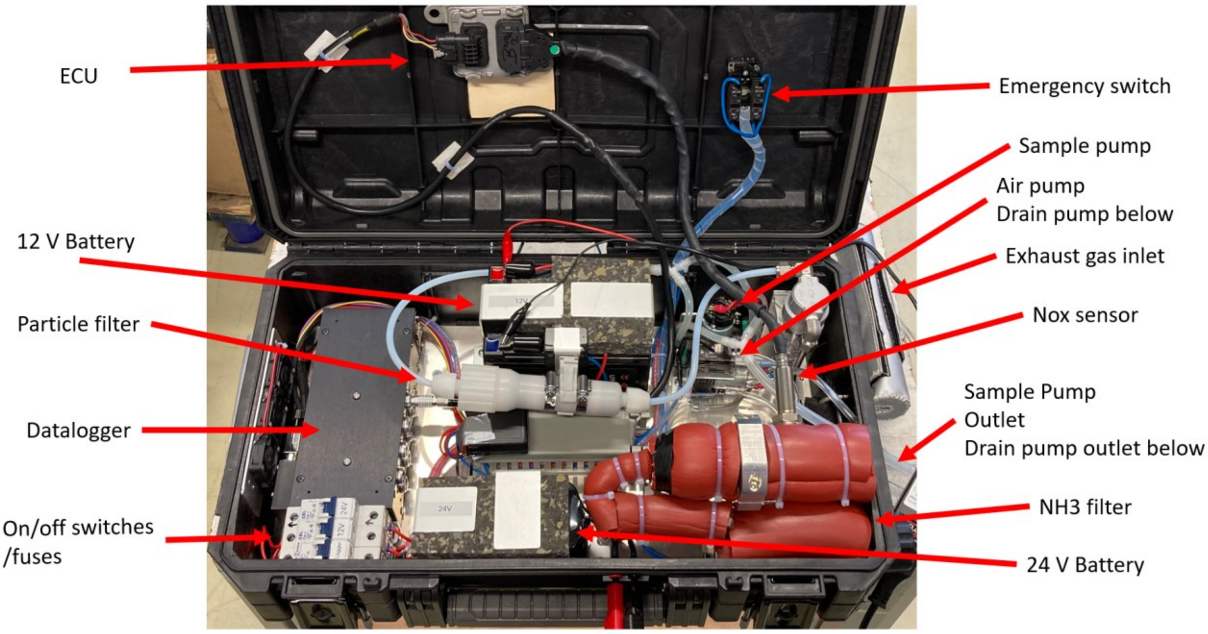


Figure 6-3: Horiba SEMS Unit

Assessment regarding Benefit and Disadvantage

+ Low weight and small size.
+ Fast warm up.
+ Attachment with straps to facilitate mounting on different types of vehicles.
- Only NO_x measurement possible at the moment.

6.2.2 HORIBA PTFM

The HORIBA Pitot Flow Meter (PTFM) determines the exhaust gas mass flow, compliant with EU RDE-LDV Legislation. The Pitot Flow Meter employs measurement of temperature and pressure to determine the exhaust flow rate. One SEMS unit and the PEMS will be equipped with the required modules to measure the mass flow rate. Two different sizes can be used for 2 and 4 m³/min to extend the accuracy for smaller vehicles.

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101056777

Assessment regarding Benefit and Disadvantage

+ High accuracy.
+ Exhaust mass flow can be measured.
+ Standardized equipment.
- Exhaust mass flow measurement sensitive to pressure pulsations. Lower accuracy for single cylinder, short exhaust pipe and at low mass flow.
- Exhaust flow measurement needs a connection between exhaust muffler and PTFM device which can be difficult to establish.

6.2.3 EMISIA ReTEMS

EMISIA has developed a prototype SEMS, named ReTEMS (Real Time Emissions Measurement System), a device capable of measuring the CO, CO_2, NO and BCPM concentration of exhaust gases. The ReTEMS design aimed at a compact & lightweight device at a low cost, which would be possible to install on a motorcycle, to measure its emissions while it is being driven in the real world.

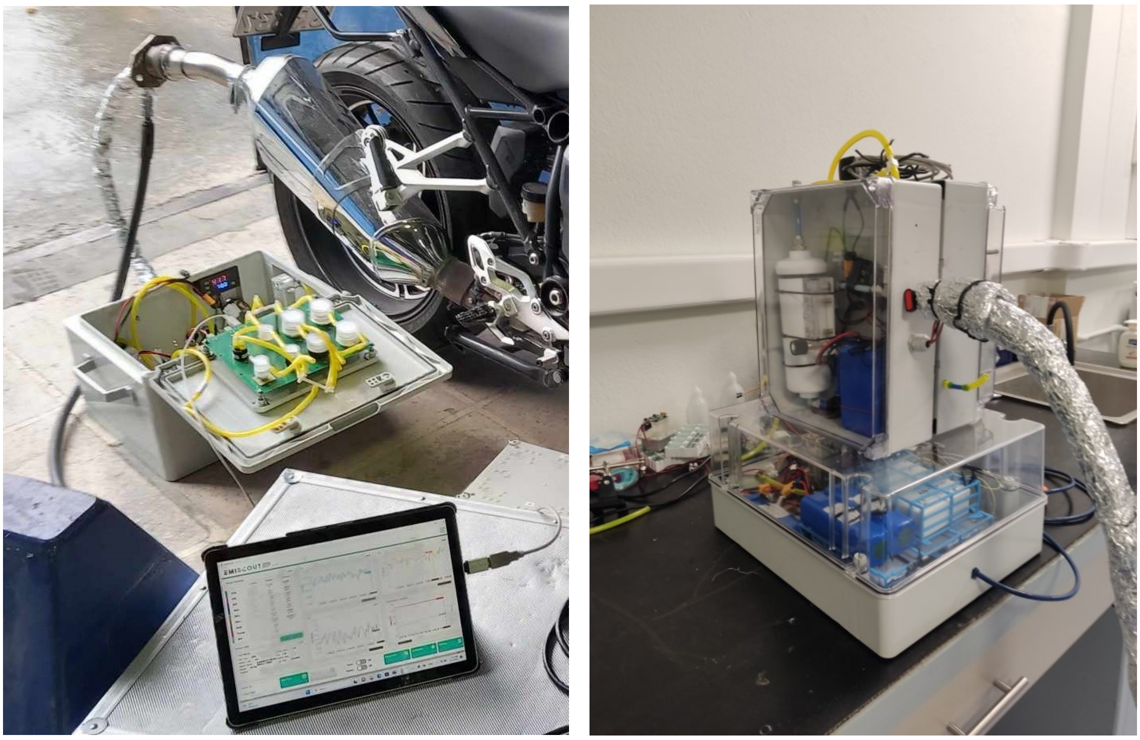


Figure 6-4: EMISIA ReTEMS Unit

The emission measurement components of the ReTEMS are the following:

- Commercial electrochemical sensors for measuring CO and NO gases concentration.
- Commercial NDIR analyser for measuring CO_2 gas concentration.
- Prototype optoacoustic sensor for measuring BCPM concentration, developed through the EU Grant Project RSENSE. The BC sensor comprises a novel ellipsoid chamber, a QTF as detector and a commercial LD being a low-cost portable sensor for real-time exhaust measurements.

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101056777

The ReTEMS also includes:

- A laptop which is used to control the sensors and record their output.
- A 12V Li-ion battery for independent power supply.
- Heated sampling line.
- 2x sample pumps.
- Adjustable sample dilution, with ambient air, set to ~1:10 for motorcycles.
- Ambient conditions sensors (temperature, humidity).
- GPS receiver.
- Capability to connect with external OBD data logger for exhaust flow calculations.

Other ReTEMS specifications:

- 1 Hz recording
- Sampling flow 0.5-2 L/min
- CO: 0-10,000 ppm
- NO: 0-5,000 ppm
- CO_2: 0-100%
- BCPM: 5-10000 μg/m^3

6.2.4 CZU FTIR

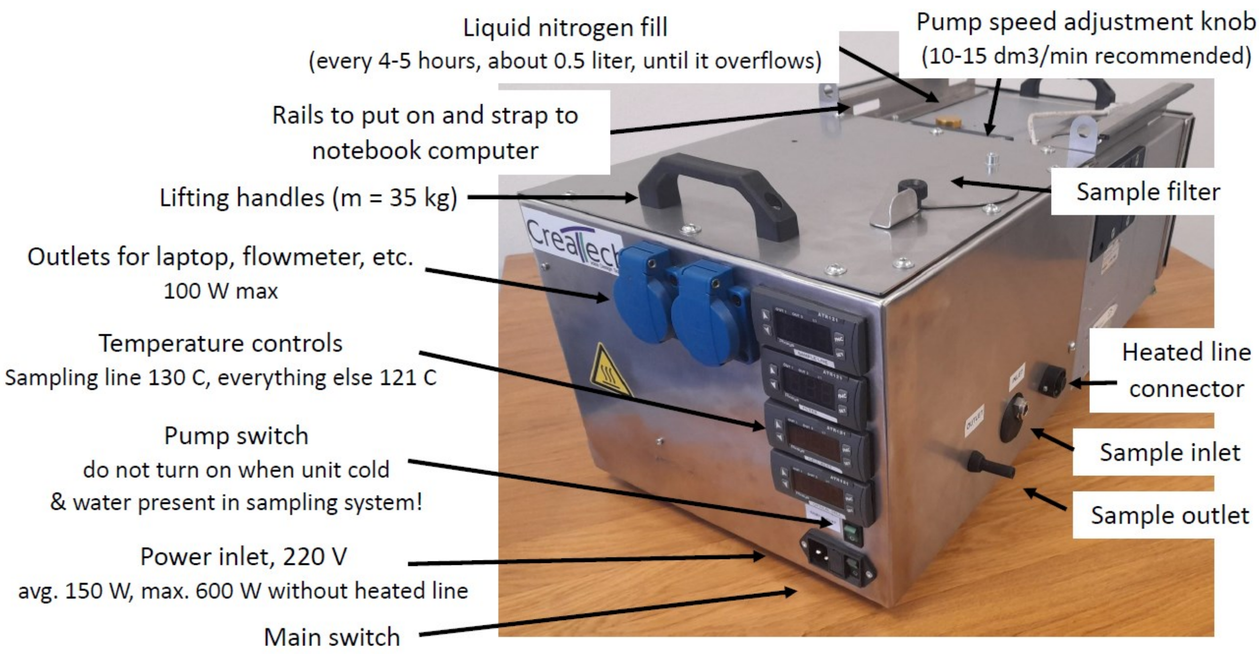


Figure 6-5: CZU FTIR Unit

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101056777

Before the measurement:

1. Make sure the pump switch is off. Turn on the main switch.
2. Fill liquid nitrogen using a funnel with a tube until droplets of liquid nitrogen flow out; about 0.5 dm^3 is needed.
3. About 20 minutes required for temperature stabilization, 30 minutes recommended. Check the temperature regularly to avoid "over-run".
4. On the notebook, run the "OPUS GA New" software.
5. Hit "connect" button on upper right part of software screen.
6. Hit "align" button. Read the signal intensity value, should be 20-26, if less, you have dirty optics. Hit "stop align".
7. From the list of compounds on the left, unclick compounds you do not absolutely need to have computed online and plotted.
8. Run a short test to check the functionality.
9. Do not leave the instrument on without supervision for extended periods (i.e., overnight).

To start the test:

1. Check temperatures (cell 121 °C, cell inlet 121 °C, filter 125 C, sampling line 130 °C).
2. Top off liquid nitrogen if > 4 hours before last fill.
3. Hit "start" button. Choose the directory where to save data.
4. A maximum of 10 000 frames of data (4 000 seconds) is recorded. If you need more, hit "start" button again.

To end the test:

1. Hit "stop" button.

Shutdown at the end of the measurement:

1. Let the instrument sample clean air (ambient air is typically fine) for 10-15 minutes.
2. Move data files to D: drive and to an external drive for backup.
3. Turn off the pump.
4. Turn off the main switch when done and leaving for the day.

This instrument uses aggressive power, thermal and space management to keep the average power consumption at 120-150 W. The instrument surfaces can reach 50-60 °C. Do not put anything on the instrument. DO NOT LEAVE THE INSTRUMENT ON unattended.

Assessment regarding Benefit and Disadvantage

+ High sensitivity.
+ Rapid measurement.
+ Multi-component analysis.
- Liquid nitrogen needed.
- High power consumption.
- Chunky.

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101056777

6.4 IFP Energies New REAL-e SEMS

6.4.1 General Overview

Figure 6-6: REAL-e SEMS Unit.

REAL-e (Figure 6-6) has been developed at IFP Energies Nouvelles since 2017. It has been imagined and designed as a Smart Emission System: easy-to-fit, easy-to-run and cost-effective. It has been built with PTI equipment and in-house components to keep good performance / cost ratio. By combining physical gas analysers and simplicity of implementation (no exhaust flow measurement, data enhanced by modelling), this system aims to simplify and extend on-board measurement. Its main characteristics are detailed Table 6-3.

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101056777

Table 6-3: Main characteristics of REAL-e SEMS Unit

[CO_2]	Heated NDIR1 (from PTI)	0-20% (0.4% or 4%)
[HC]	Heated NDIR1 (from PTI)	0-20000 ppm (10 ppm or 5%)
[CO]	Heated NDIR1 (from PTI)	0-15% (0.03% or 3%)
[O_2]	ECC2 (from PTI)	0-25% (0.1 or 3%)
[NO_x]	ECC2 (from PTI)	0-5000 ppm (5ppm or 5%)
[NO]	UV-DOAS (in house-development)	0-1000 ppm (1 ppm or 1%)
[NO_2]	UV-DOAS (in house-development)	0-500 ppm (10 ppm or 10%)
[NH_3]	UV-DOAS (in house-development)	0-1000 ppm (1 ppm or 1%)
[PN]	Extended DC (from PTI)	5000-5000000 #/cm^3 Detection limit: 1000 #/cm^3 Resolution: 1000 #/cm^3
Exhaust Flow Meter	From model	
Emission mass flow	From consumption model and pollutant over CO_2 ratio	
GPS info	OBD Dongle	
Weather info	Web service	
OBD data	OBD Dongle	
Need of span gas	Every 6 months	

[1] Non-Dispersive InfraRed
[2] Electro Chemical Cell

In the following parts, will be detailed the calculation principle that is used to do without an exhaust-flow meter and the different results that demonstrate the relevance of the approach.

6.4.2 Pollutant mass flow calculation coupling measurement and modelling [5]

One of the main constraints of state-of-the-art pollutant on-board measurement is the measurement of exhaust mass flow to convert pollutant measurement from concentration to mass flow. With REAL-e, we use a methodology based on the monitoring of instantaneous pollutants over CO_2 concentration ratio and the estimation of CO_2 emissions (CO_2 est.). The CO_2 estimation comes from the addition of two bricks:

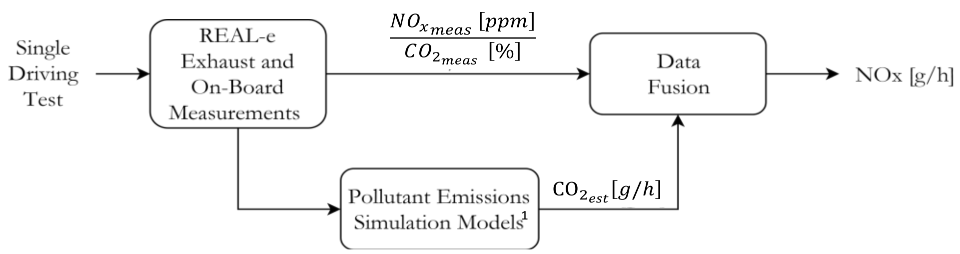
- Vehicle dynamics model: using the GNSS trip signals (vehicle speed and altitude), this model is able to estimate the engine power. First, power at the wheels is computed through longitudinal dynamics equations. Then, with the transmission efficiency and the reduction ratio between the wheel and the engine crankshaft, the velocity and torque from wheels can be converted into engine speed and torque. Available OBD signals (engine speed, etc.) help to refine the models and specifically the transmission layout.
- Internal physical quantities model: this part of the model evaluates the internal physical quantities for the current engine operating point, based on the following basic assumptions:
    - Maximum torque curve of the engine estimated from maximum torque, maximum power and air-path architecture.

[5] Dégeilh P., Kermani J., Rodríguez S., Frobert A. et al.; REAL-e: Robust and affordable IoT solution for market surveillance. *23rd Transport and Air Pollution Conference*, Thessaloniki, 2019.

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101056777

- Friction Mean Effective Pressure (FMEP) generic law (function of engine speed) depending on engine architecture.
- Constant gross indicated efficiency.
- Fuel air equivalence ratio equal to 1 in spark ignition engine (except at high load where it increases linearly with load) and varying between two values for compression ignition engine.
- EGR (Exhaust gas rate) fraction is, when it makes sense, assumed for each point of the engine map.

These assumptions allow to calculate the Pumping Mean Effective Pressure, and later, fuel consumption, total intake mass flow rate and exhaust mass flow which take into consideration the EGR and the hybridization level if necessary, and pressure and temperature conditions, for the instantaneous engine operating point. The CO_2 emissions are directly calculated from the fuel consumption. As introduced previously, this estimation of CO_2 is used to calculate pollutant emissions from pollutant over CO_2 concentration ratio, as depicted in Figure 6-7.



$$\boldsymbol{NOx\ RealE}\left[\frac{g}{h}\right] = \left(\frac{NO_{x_{meas}}\,[ppm]}{CO_{2_{meas}}\,[\%]}\right) * \mathrm{K} * \mathrm{CO}_{2_{est}}[g/h]$$

Figure 6-7: Estimation of CO_2

6.4.3 Raw measurements & final measurement validations [5,6,7]

The raw concentration measurements of REAL-e have been compared to the ones from a PEMS on a panel of passenger car vehicles driven on different trips and driving styles (RDE-like around 80 km and 90 minutes, short urban trips around 7 km and 15 to 20 minutes). Figure 6-8 shows the results of this comparison, with the density plot of all the measurements performed on the test campaign for CO_2 and NOx for more than 30 trips and 1200 km driven. In addition, performance indexes have been computed in the form of the coefficient of the trend curve, showing a good match between the two measurement devices and also the standard deviation that remains low regarding the range of measurement. Results are similar for CO and PN measurement.

---

[6] Dégeilh P., Kermani J., Sery J., Michel P., Study of Euro 6d-TEMP emissions - IFPEN for DGEC: Summary report. [Research Report], French Ministry of the Ecological Transition, 2020. ⟨hal-03632915⟩.

[7] P. Dégeilh, J. Kermani, S. Rodriguez and A. Frobert, Emission Monitoring for used cars: Evaluation of On-Road Testing, 25th Transport and Air Pollution Conference, Göteborg, 2023.

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101056777

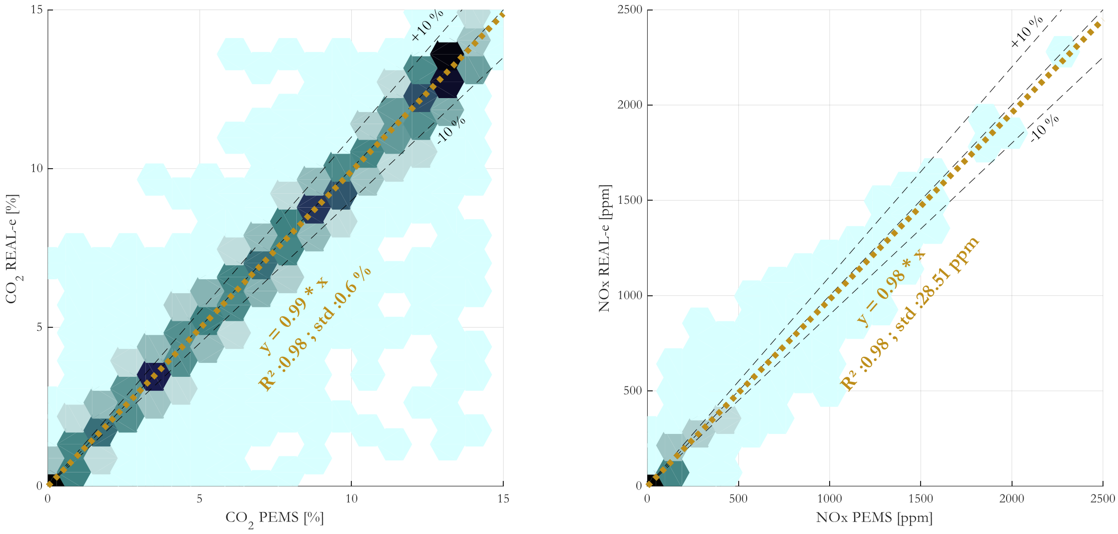


Figure 6-8: Results of the comparison between the raw concentration measurements of REAL-e and the ones from a PEMS on a panel of passenger car vehicles driven on different trips and driving styles (RDE-like around 80 km and 90 minutes, short urban trips around 7 km and 15 to 20 minutes)

System has been used during a high range study for the French Ministry of Ecological Transition in 2020 (22 Euro 6d Temp passenger cars). During this campaign, REAL-e has been used as a backup with a conventional PEMS. The comparison (limited here to NO_x and to Diesel cars – available for CO and NH_3 as well) showed that the use of REAL-e instead of PEMS could have led to similar results. This is illustrated in Figure 6-9: it presents the NOx levels measured for 8 Diesel cars (DV1 to DV8) during the overall test campaign. Each dot is an individual test. The boxplots in dark green represents PEMS results, the light green ones are obtained with REAL-e.

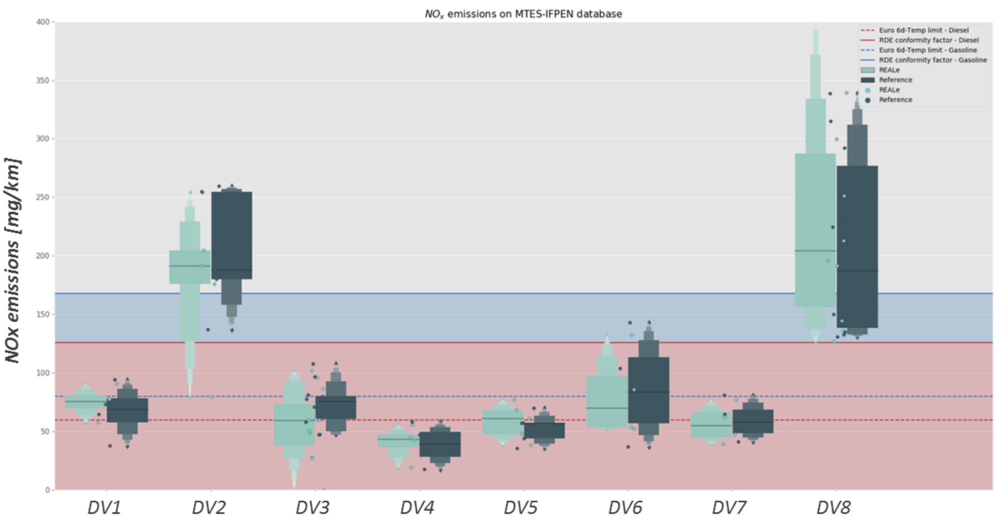


Figure 6-9: PEMS and REAL-e NOx levels measured for 8 Diesel cars (DV1 to DV8)

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101056777

6.4.3 Assessment regarding Benefits and Disadvantages

+ Easy to fit (no EFM).
+ Electrically autonomous.
+ Validated on large test campaigns on passenger cars.
+ Robust measurement systems.
+ Standardized equipment.
+ Low calibration effort needed.
- REAL-e is a research tool and not an industrial device.
- Raw measurement precision is lower than on references devices.
- Adaptation and validation for category L vehicles is underway as part of the LENS project.

6.5 Additional Equipment / OBD/CAN – Tools

6.5.1 Online Can-data logging integrated into measurement platform

Two primary approaches for leveraging OBD/CAN devices within Project LENS provide valuable options for data collection. The first approach involves using online data logging tools like Peak CAN or Vector, which can be integrated into measurement devices such as PEMS or SEMS or used as standalone devices paired with a notebook for logging purposes. This approach allows for real-time data retrieval and offers a wealth of information. However, it requires access to the DBC (CAN database) files provided by the OEM to accurately interpret the data.

6.5.2 Stand-alone Online Can-data logging

The second approach utilizes offline devices like standalone CAN loggers such as the CSS Datalogger, which stores data on an SD card. Like online tools, these devices are compatible with OBD and CAN protocols but with the disadvantage of data collection without real-time connectivity. Both approaches are particularly suitable for newer vehicles compliant with EU4 regulations and beyond, with data quality and availability varying depending on the vehicle's model year and manufacturer. These tools enable more comprehensive data capture, with higher accuracy and frequency, compared to OBD alone, making them valuable assets in emissions testing and data analysis.

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101056777