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Executive summary

Standardized emission measurement tools like PEMS are expensive and laborious, and therefore not suitable to be applied in a large fleet. Beyond PEMS, there are several other methods to monitor vehicle emissions using standard (cheap) sensors, monitoring boxes and data channels. The aim of this report is to demonstrate the validity of these methods and explore how they can be used as direct feedback tool towards the vehicle user, e.g. with a display, LED or a smartphone application.

Three paths were defined and solutions were delivered:

1. A device to extract data and signals from the CAN and/or directly from the OEM sensors: NO_x feedback tool.
2. A device that makes use of installed (non-OEM) sensors to measure and use the emission concentration: Crossyn sensor data logger.
3. A 'mini-PEMS' consisting of cheap testing solutions to measure different components, incl. non-regulated emissions: Particle sensor, Mini-PEMS and portable FTIR.

The NO_x feedback tool is connected to the OBD of the vehicle and a bar of LEDs. It provides drivers insight into the real-time NO_x emission of their vehicle. It is suitable for Euro 6 Diesel vehicles, from which it reads out the NO_x sensor data. Validation tests show strong correlation between NO_x emissions and LED feedback.

The Crossyn system is connected to installed sensors as well as the OBD of the vehicle. The purpose is to log the data received from both channels. Validation shows that the system is capable of correctly communicating with a UNINOX NO_x/O₂ sensor. It is suitable for vehicles with OBD.

The Particle sensor, Mini-PEMS and the portable FTIR are all part of the third path of measuring vehicle emissions. The particle sensor uses parts of a cheap smoke detector. Validation shows that the system is capable of detecting a severely damaged DPF as well as a removed DPF.

The Mini-PEMS design builds on a simple setup by Vojtisek-Lom and Cobb. This design was expanded by addition of an electrochemical sensor to measure NO₂, and by low-cost PM sensors using light scattering and/or measuring ionization chamber, as explained earlier, among other things. Validation shows that Mini-PEMS and laboratory results are in general agreement for all measured gaseous pollutants, with particulate matter being subject to additional evaluation. It is suited for vehicles with small engines, e.g. mopeds.

The portable FTIR is proposed as a universal tool for measurement of nearly all gaseous pollutants by a single instrument. Validation shows a general agreement among a type-approval PEMS (AVL MOVE) and a laboratory FTIR (MKS 2030). It is suited as an alternative to PEMS.

These cheap and simple monitoring solutions create options for pilots, for example, during public events. Either the equipment can be installed in the vehicles of a few tens of drivers or the equipment can be used in fairground events.

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Definitions & Abbreviations

CAN	Controller Area Network
COPERT	Computer Programme to calculate Emissions from Road Transport
DoA	Description of Action, a.k.a. DoW
DoW	Description of Work, a.k.a. DoA
EC	European Commission
FTIR	Fourier Transform InfraRed spectroscopy/spectrometer
HBEFA	Handbook Emission Factors for Road Transport
LED	Light Emitting Diode
OBD	On-Board Diagnostics
OEM	Original Equipment Manufacturer
RGB	Red Green Blue
PEMS	Portable Emission Measurement System
PM	Particle Mass/ Particle Matter
SEMS	Smart Emission Measurement System
WP	Work Package

Introduction

1.1 Background uCARE

With four million people dying annually due to outdoor pollution, improvement of air quality has become one of society's main challenges. In Europe, traffic and transport have a large effect on air quality, specifically passenger cars and commercial vehicles and to a lesser extent non-road mobile machinery. While technical improvements and more stringent legislation have had a significant impact, traffic and transport emissions are still too high and air quality is still poor. Although the use of electric and other zero-emission propulsion technologies may drastically reduce the pollutant exhaust emissions from traffic, the slow introduction of such vehicles as well as the trend of increasing vehicle lifetimes means that vehicles with internal combustion engines are expected to dominate the fleet beyond 2030. This project is the first opportunity to improve emissions of vehicles, not by improving vehicle technology, but by actively involving vehicle users and enabling their contribution to clean driving.

So far, expertise on pollutant emissions has mainly been used to advise European policy makers on limited effectiveness of emission legislation (through real-world emission factors such as HBEFA and COPERT) and how to reduce traffic and transport pollutant emissions. The numerous mitigation methods are rarely extended to include the perspectives of users uCARE enables a next essential step: providing user targeted emission reduction measures. These measures will be implemented and evaluated in real-life pilot projects.

The overall aim of uCARE is *to reduce the overall pollutant emissions of the existing combustion engine vehicle fleet by providing vehicle users with simple and effective tools to decrease their individual emissions and to support stakeholders with an interest in local air quality in selecting feasible intervention strategies that lead to the desired user behaviour*. The overall aim is accompanied by the following objectives:

1. To identify **user-influenced vehicle emission aspects** (such as driving behaviour and vehicle component choice).
2. To determine the **emission reduction potential** of each vehicle emission aspect with help of the uCARE model developed within a toolbox.
3. To develop a **toolbox**, containing models and emission reduction measures, that enables stakeholders to identify the most appropriate intervention strategies that reflect the specific users and their motivation.
4. **Support policy makers** and other **stakeholders with an interest in air quality**, such as municipalities and branch organizations, **in identifying intervention strategies** that translate the measures into desired behaviour of the user.
5. **To test and evaluate** intervention strategies in a set of pilot projects conducted with various target user groups in at least four European countries. The pilot projects illustrate effectiveness and feasibility of the toolbox and intervention strategies developed on its basis.
6. Perform an **impact assessment** of the intervention strategies effectiveness, in terms of cost, penetration, achieved emission reduction and lasting effects.
7. **Actively feed** European cities and international parties with uCARE learning and results, via awareness raising campaigns, communication tools, interactive web application and other dissemination activities. Open access to the broad public to the toolbox, data and developed tools.
8. Summarise the findings **in blueprints for rolling out** different user-oriented emission reduction programmes, based on successful pilots.

This report is part of WP1: the assessment of the user impact on emissions. uCARE will give direct feedback to motivated vehicle users that want to reduce their ecological footprint. For this purpose, (relatively) cheap and simple monitoring solutions are required.

This document is the output of Task 1.3 and will be relevant for WP2 and WP3, i.e. in the use of a feedback app for direct interaction with the vehicle user.

Standardized emission measurement tools like PEMS are expensive and laborious, and therefore not suitable to be applied in a large fleet. Beyond PEMS, there are several other methods to monitor vehicle emissions using standard (cheap) sensors, monitoring boxes and data channels. There are some solutions available, such as the SEMS [1] and the AutoPi [2]. However, these solutions either do not offer the required features and/or are too expensive for wide usage. Therefore, new tools are developed and demonstrated in Task 1.3. The aim of this task is to extend the available solutions, demonstrate the validity of these methods and explore how they can be used as direct feedback tool towards the vehicle user, e.g. with a display, LED or a smartphone application.

1. In the first route, a device will be used to extract data and signals from the CAN and/or directly from the OEM sensors. This can be (a combination of) an OBD dongle, a CAN sensor read-out or other.
2. The second route makes use of installed (non-OEM) sensors to measure and use the emission concentration only.
3. A third route is the development of a 'mini-PEMS' consisting of cheap testing solutions to measure different components, incl. non-regulated emissions. Such systems are intended for showcases, validation testing, and events included in pilot programs.

The demonstration of the equipment will be done using a defined test setup and validating the measurement outcomes to PEMS, SEMS or laboratory equipment. The systems are tested and validated in Task 1.6 if additional validation is needed, ready to be used in pilot programs in WP3, as proofs of concept.

1.2 Purpose of the document

This report describes three monitoring solutions:

- **emission measurements using CAN interfaces**

In the first route, a device will be used to extract data and signals from the CAN and/or directly from the OEM sensors. This can be (a combination of) an OBD dongle, a CAN sensor read-out or other.

- **emission measurements using sensor solutions**

The second route makes use of installed (non-OEM) sensors to measure and use the emission concentration.

- **emission measurements using 'mini-PEMS'**

The third and final route is the development of a collection of innovative, small and low-cost emissions monitoring devices to measure different components, incl. non-regulated emissions.

1.3 Document Structure

The chapters 2, 3 and 4 each describe one of the monitoring solutions. Within each chapter the following structure is used:

- x.1 Target use of and design requirements for the solution
- x.2 Technical description of the solution
- x.3 Validation of the solution
- x.4 Conclusions regarding the applicability of the solution

1.4 Deviations from original DoW

1.4.1 Description of work related to deliverable as given in DoW

This deliverable describes the [cheap and simple monitoring] solutions: method, validation, and test report.

1.4.2 Time deviations from original DoW

The deliverable was produced with a limited delay, mainly due to the COVID-19 situation that delayed some basic validation work.

1.4.3 Content deviations from original DoW

None.

2 Emission measurements using CAN interfaces

The solution presented in this chapter involves a device to extract data and signals from the Controller Area Network (CAN) and/or directly from the Original Equipment Manufacturer (OEM) sensors. The development started on a device that gives the driver real-time feedback on the NO_x emissions of the vehicle.

2.1 Target use of and design requirements

When it comes to reducing harmful tailpipe emissions (e.g. NO_x or Particle Matter (PM)) during daily driving, there are a lot of generic driving instructions that can be found on the internet that would achieve exactly that. But there is no information whether your actions really reduce these emissions. Moreover, it could be hard to find an optimal driving style for your specific vehicle. Measuring these tailpipe emissions with additional sensory will be costly. Therefore we thought of a method to achieve the same result, using the vehicle's sensor information that is available on the OBD connector of your vehicle. Modern vehicles are equipped with a CAN-bus to interchange vehicle data, and many modern diesel vehicles are also equipped with NO_x-, oxygen- or even PM-sensors. Usually, they provide the on-board diagnostics information on the technical functioning of the after treatment systems, but we will try to use this information to determine actual real-time emissions.

2.2 Technical description

The NO_x indicator will be built of a micro controller, CAN-bus shield, On Board Diagnostics (OBD) -cable and a Red Green Blue (RGB) Light Emitting Diode (LED) bar. The micro controller will request sensor information from the vehicle, utilizing a CAN shield that is connected via the OBD cable to the OBD port of the car. The output of the microcontroller is connected to the RGB LED bar via a 3-wire cable as shown on the images. For the robustness of the system, it is best to build the micro controller and CAN shield within an enclosure to prevent it from damaging.



Figure 2-1: OBD cable



Figure 2-2: LED bar



Figure 2-3: Electronics in enclosing

2.2.1 Calculation and output

The LED bar contains 10 RGB LEDs which are driven by the software on the micro controller.

1	2	3	4	5	6	7	8	9	10
Gn	Gn	Gn	Yw	Yw	Or	Or	Rd	Rd	Rd

Figure 2-4: NOx tool LED colours

The amount of LEDs that will light up, will vary when current NOx emissions versus the recent history changes. The current calculation that is used in the code is;

$$n_{leds} = (int) 3 * \frac{avg\ NOx\ 5s}{avg\ NOx\ 200s}$$

This will make the LED bar float around 3 green LEDs as long as the 5 second average NOx output is equal to the long 200 second history. The number of LEDs are set to 1 if the result of the calculation becomes zero, so that the driver can always see that the system is still working. The long history for NOx helps to identify a rising or falling signal in the current NOx because it just slowly adapts to an increase or decrease of NOx.

2.3 Validation

To validate the output of the LEDs, 2 situations will be discussed; an immediate increase and a decrease of NOx emission that is observed from the OBD data.

The first situation is a sudden increase of NOx measured by the vehicle, due to an acceleration. The average NOx while idling was stable, e.g., 120 ppm. If the signal increases with several hundreds of ppm, the (short) 5s average will increase quickly. The long history of 200 seconds will only slight increase due to the higher concentrations. This will make the number of LEDs that ignite also increase rapidly as shown in the graph.

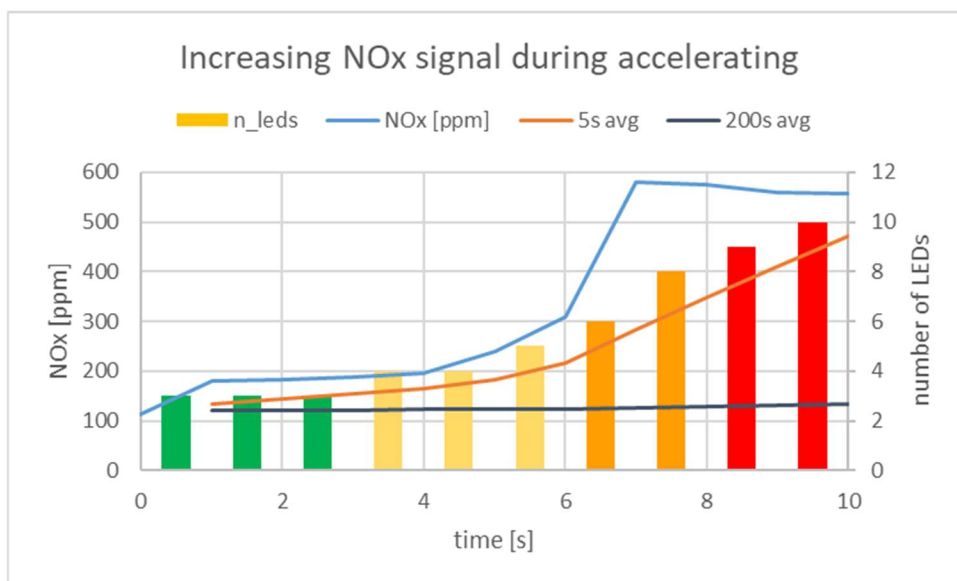


Figure 2-5: NOx and LEDs during acceleration

The second situation is where the driver is motoring, e.g., during braking towards a red traffic light. The short history will, due to the low NO_x output of the engine, rapidly go towards zero. The long history, however, is only slightly affected by the almost-zero output. This makes the numerator in the equation become small, and the denominator become large. The result of the equation is therefore a very low number (almost zero) which is set to 1 by an if-statement.

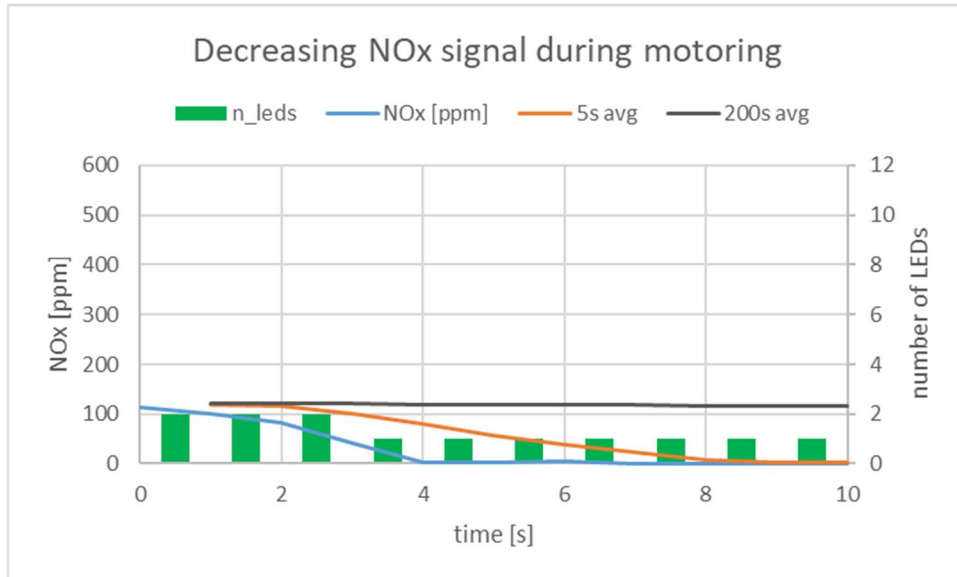


Figure 2-6: NO_x and LEDs during motoring

The tool is designed to help drivers adapt their driving behaviour to decrease their harmful emissions. It is also important to validate whether the output of the LEDs shows a different output, based on different behaviour of the driver. In the next figure three accelerations are presented with different behaviour. The first one has a smooth acceleration. The second one is less smooth and the third acceleration is aggressive.

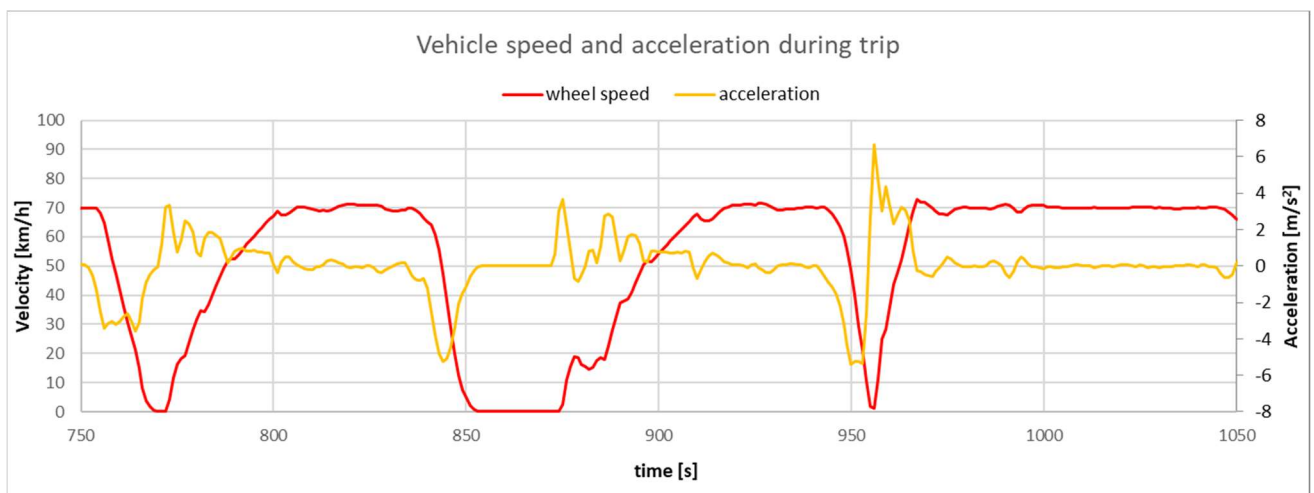


Figure 2-7: Velocity and acceleration over time for a test trip

From this data set, the 200s average, 5s average and number of LEDs that light up are calculated. It can be observed, that the smoothest acceleration, gives only a slight increase of LEDs in the yellow range with only one spike towards the orange area. The second acceleration is more bumpy and also has a deceleration in between the gear shifts (1 to 2 and 4 to 5). It results in more LEDs to light up, towards 10 LEDs. The third acceleration is

clearly more aggressive. Immediately after the run-off, the LEDs rise towards the 10 LEDs (red area). The tenth LED stays on until the 70 km/h is reached and the throttle is released. Within a few seconds the LED count has returned to 2 to 4 LEDs. During cruising 70 km/h the LED bar remains stable at 3 LEDs.

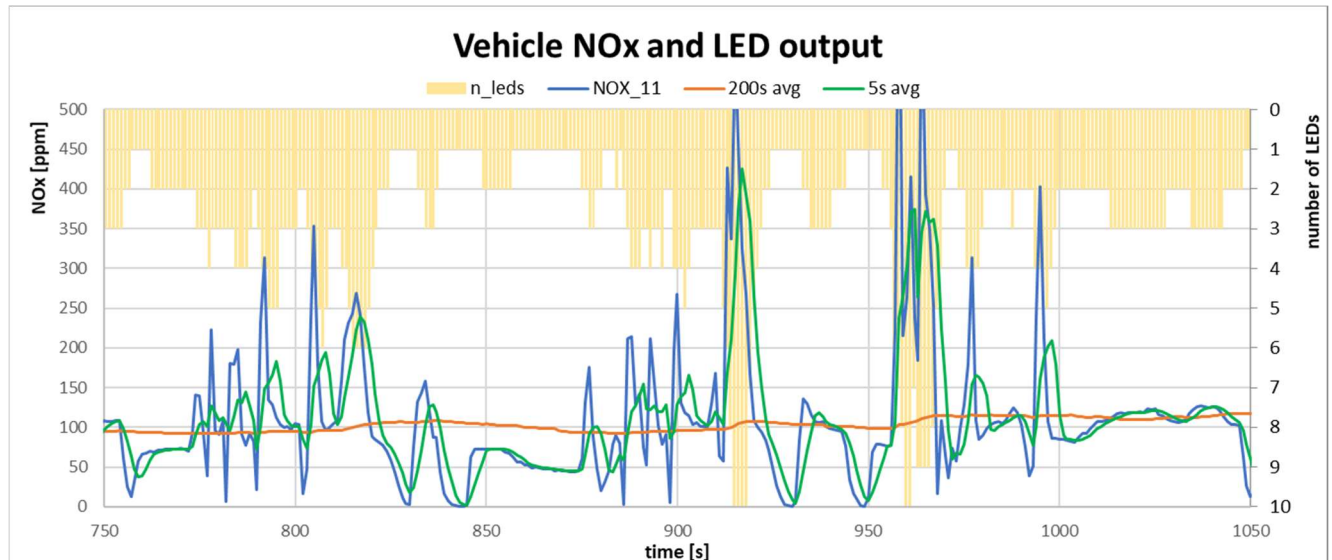


Figure 2-8: NOx and LEDs over time for a test trip

2.4 Applicability

The tool will focus on using information from the combined NO_x/oxygen sensor that is used in Euro 6 diesel cars to provide the driver information on his/her real-time NO_x emissions, displayed on an easy to read LED light bar.

This NO_x feedback tool can be put to use in a uCARE pilot to study the change in behaviour with direct feedback. This could then also be compared to behavioural changes induced by feedback after a trip.

Another use of this tool is as part of a driver training, either by a driving school or as a post-exam eco-driving training. The direct feedback offers a clear insight into the correlation between driving behaviour and exhaust emission.

3 Emission measurements using sensor solutions

The solution presented in this chapter involves installed (non-OEM) sensors to measure and use the emission concentration. The development contained expanding the capabilities of the current Crossyn hardware: reading out installed sensors.

3.1 Target use of and design requirements

The target of this sensor based solution is to collect a minimum of five data signals in real-world driving situations on 1 Hz for at least 20 vehicles.

The selected data signals for this solution are:

- NO_x;
- Vehicle speed;
- Engine speed;
- Engine coolant temperature; and
- Road gradient.

3.2 Technical description

The (OEM-)sensors based solution features a dual SIM, GNSS/GSM/Bluetooth terminal with RS232/RS485 serial communication interfaces, designed to read CAN data from vehicles and specialised transport (the FMB640 device), combined with two CAN Inserter devices, programmed by Crossyn to send messages to the CAN bus and (OEM-)sensors.

The FMB640 device is equipped with a SIM card and is necessary to transmit the data to the platform of Crossyn. However, the downside of the FMB640 – and, therefore, the challenge for this specific project – was that this device is only able to 'listen' to the CAN bus. For controlling the sensors though (e.g. warming them up, if needed), and to be able to collect the data signals listed above (especially the NO_x-values), it is also necessary to be able to send commands to the CAN bus.

Therefore, a combined solution as shown in the technical design below, has been developed.

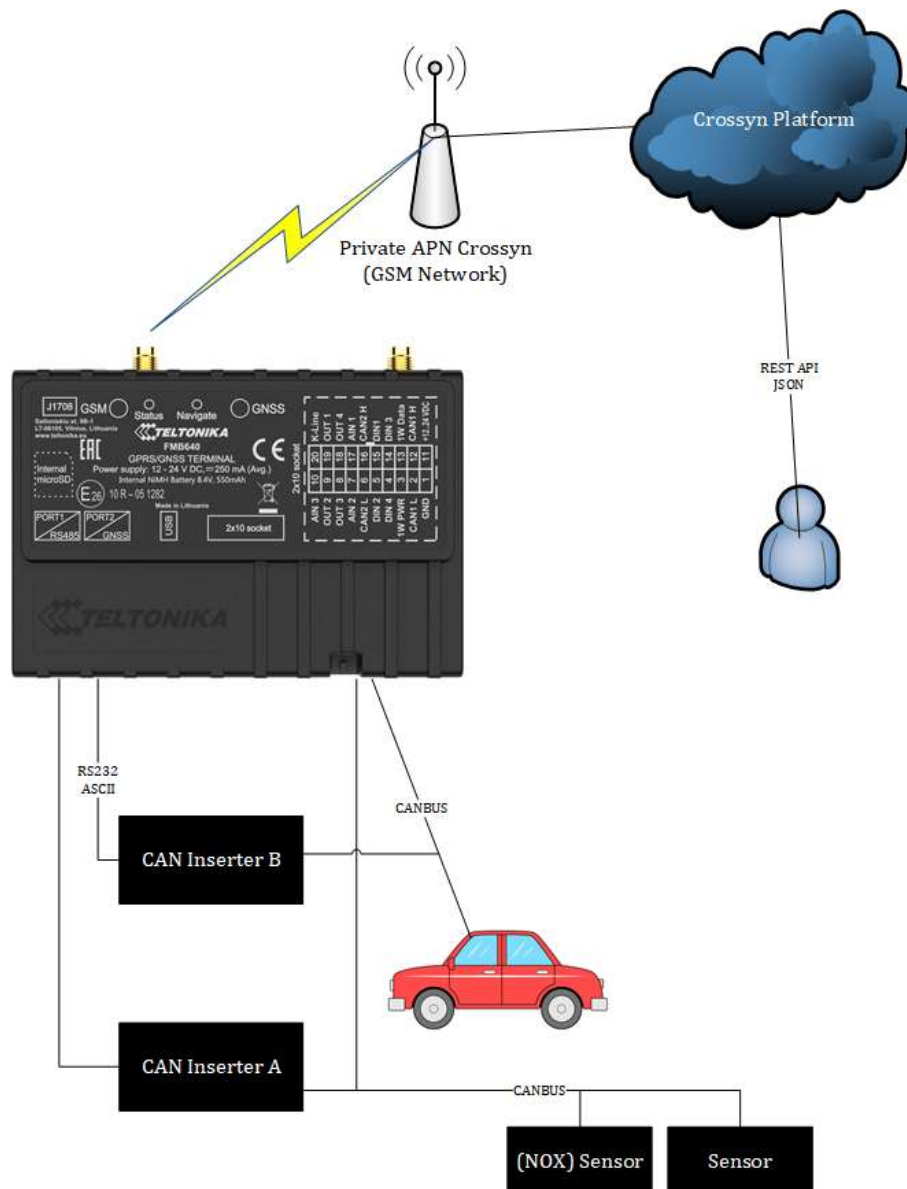


Figure 3-1: Crosssyn system schematics

The CAN Inserter devices are simple devices that can be programmed through a serial port (RS232) with ASCII commands. Both devices consist of the same hardware and can be instructed (via 'commands') to send data on the CAN bus to a specified address and to keep repeating this command every set number of milliseconds. Depending on the configuration, the CAN Inserter devices should be connected either to the CAN bus of the car or the CAN bus of the sensors. Instructions for the CAN Inserter devices can be sent from the platform of Crosssyn. Authorised persons will be enabled to program the settings through a POST API.

To receive the answer, the Manual CAN IO functionality of the FMB640 will be used. The parameters of the Manual CAN IO can be set by sending messages to the FMB640, again from the platform of Crosssyn, via a POST API.

Collected data signals will be securely transmitted via APN to Crosssyn's open and ISO 27001-certified platform, and will be stored as JSON-messages that can be requested via API.

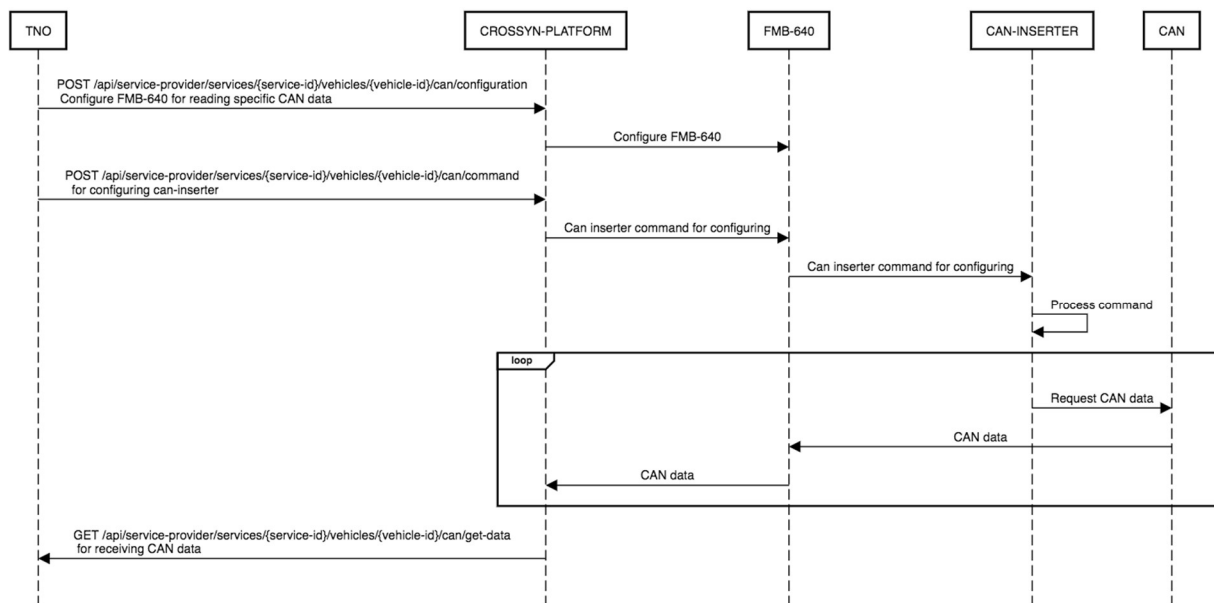


Figure 3-2: Communication diagram of the system

3.3 Validation

A test has been carried out with a 1.0 version of Crossyn's (OEM-)sensors based solution and TNO's SEMS-equipped Volkswagen Caddy.

Despite the fact that the validation test revealed some minor hardware and software bugs (which have already been fixed at the moment of writing this paragraph), the test has shown that the solution is suitable for collecting the data signals referred to in paragraph 2.1 in real-world driving situations on 1 Hz.

3.3.1 NO_x sensor validation

Validating the NO_x reading of the Crossyn FMB640 has been done by comparing it to that of TNO SEMS. For this test a vehicle ready-equipped with TNO SEMS, a Volkswagen Caddy, was used. The vehicle is equipped with two UNINOX NO_x/O₂ sensors mounted in the exhaust pipe. One sensor has been connected to the Crossyn FMB640, the other one to the TNO SEMS.

The Caddy was taken on a short drive, where the following data was generated. On the left the outputted data of both systems is shown. On the right is a zoom-in.

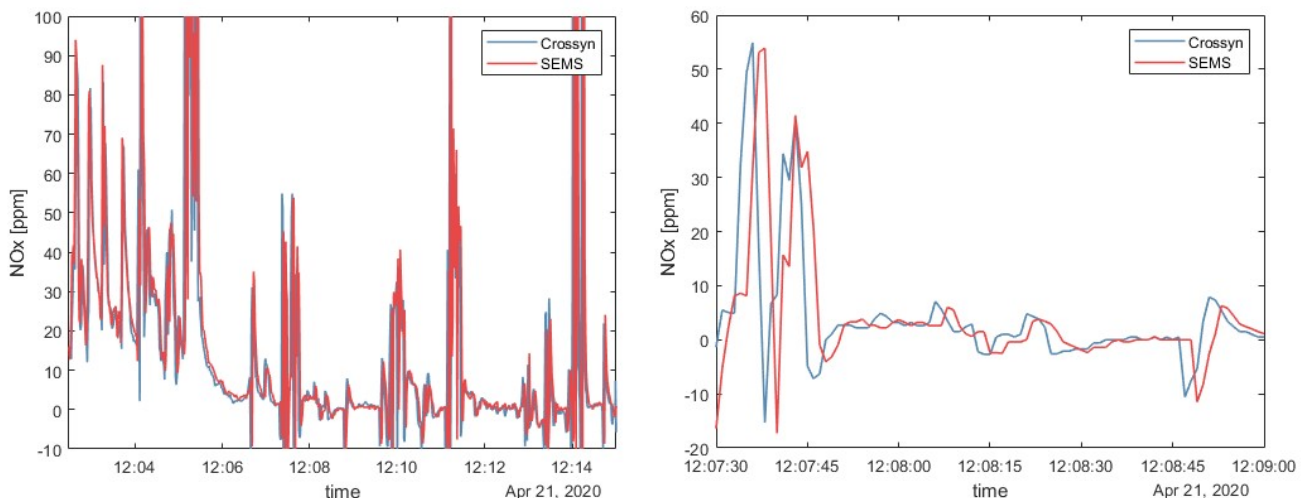


Figure 3-3: NO_x measured by SEMS and Crossyn; full trip (left) and zoom-in (right)

Looking at the results above, both systems show a greatly similar response. The trend of both signals is matching, especially when taking deviations between two sensors into account. The zoom-in (Figure 3-3, right) also reveals a time delay between both systems, where the Crossyn data seems to be earlier than the SEMS data. This delay could have various causes like sensor position, however it does not interfere with the purpose of this validation. The Crossyn system is evidently capable of correctly reading out the UNINOX NO_x/O₂ sensor.

3.4 Applicability

The (OEM-)sensors based solution can be applied in vehicles with a built-in NO_x-sensor, as well as in vehicles in which (non-OEM) NO_x-sensors are installed. The solution can be used in pilot programs to measure NO_x-emissions in real-world driving situations on 1 Hz.

This tool can be used in a uCARE pilot by analysing the data on the Crossyn platform and providing feedback to the driver. This can be done by the software built in uCARE WP2 and the feedback can be provided to the driver via e-mail or to an app on the driver's mobile phone. This tool is cut out for more complex analysis, involving multiple sensors and/or CAN signals, simultaneously.

The tools presented in this report can also be used in combination. There are of course many possibilities. To give an idea of these possibilities, we sketch one out.

In this pilot the stakeholder, a city, wants to reduce NO_x emissions and wants to provide the NO_x direct feedback tool to drivers for a period of 3-4 weeks, e.g. triggered by the purchase of a new or second hand car.

To establish the effect of this tool on the driving behavior and generated NO_x pollution, the NO_x direct feedback tool can be combined with the Crossyn monitoring tool. In this pilot this set-up is to investigate the short term and mid-term effects. Keep in mind that prior to the start of the actual monitoring pilot, the messages to the drivers aimed at change of behavior need to be tested in order for it to yield the correct/intended effect.

Week 1: Distribution of the equipment to the first 25 drivers in the pilot. Assistance with getting the Crossyn boxes up and running. NO_x direct feedback tool not installed yet.

Week 2: Baseline measurement. The drivers just drive 'as usual'.

Week 3: NOx feedback tool installed; instructions on how to use it.

Week 4-5: Continuously monitoring of the user behavior with the NOx direct feedback.

Week 6: De-installation of the NOx direct feedback tool (same configuration as week 2).
Check if behavior change remains after 1 week.

Week 7: Redistribution of the equipment to the second group of 25 drivers. Similar to week 1.

Week 8-12: As week 2-6 for the second group.

Week 13: Redistribution of the equipment to the third group of 25 drivers. Similar to week 7.

Week 14-18: As week 2-6 for the third group.

Week 19: Redistribution of the Crosssyn equipment to the first group of 25 drivers.

Week 20: Monitoring long term effect – compare with week 6 for effect 14 weeks after end of feedback.

Week 21: Redistribution of the Crosssyn equipment to the second group of 25 drivers.

Week 22: Monitoring long term effect – compare with week 12 for effect 10 weeks after end of feedback.

Week 23: Redistribution of the Crosssyn equipment to the third group of 25 drivers.

Week 24: Monitoring long term effect – compare with week 18 for effect 6 weeks after end of feedback.

The results of the behavior as monitored can be combined with a questionnaire to find out more about the driver perspective.

Based on the results of the pilot, recommendations can be provided to the city on the use of the NOx feedback tool and the estimated effect on the air quality in the long term.

4 Emission measurements using 'Mini-PEMS'

The solution presented in this chapter is the development of a mini-PEMS consisting of cheap testing solutions to measure different components, incl. non-regulated emissions. The development of these innovative, small, low-cost emissions monitoring devices proceeded on three different paths:

- 4.1 Low-cost particle sensors for vehicle inspection purposes (target cost: 100 EUR)
- 4.2 Miniaturized on-board device (Mini-PEMS) for quantitative measurement of emissions (target cost: 10 K EUR, target mass: 10 kg all-inclusive)
- 4.3 Portable FTIR analyser as a single instrument for measurement of unregulated pollutants (target cost: 100 K EUR, target mass: 100 kg all-inclusive)

4.1 Particle sensor

The first instruments from the 'Mini-PEMS' solutions are the low-cost particle sensors.

4.1.1 Target use of and design requirements

The target use of this equipment is detecting particle emissions from diesel vehicles with (or without) a Diesel Particulate Filter (DPF).

Household and industrial smoke alarms utilize two methods to detect smoke particles (aside from detecting carbon monoxide or heat): ionization chamber and light scattering. Low-cost sensors available on the market for hobby and citizen science use almost entirely rely on light scattering.

Light scattering is inexpensive and safe technology, but it is virtually insensitive to particles smaller than the wavelength of the light used. Since engine exhaust particle diameter is mostly on the order of units to tens of nanometers (nm), the method detects only relatively large aggregates hundreds of nm in diameter. The typical household smoke alarms have alarm threshold limits corresponding to a light extinction coefficient k on the order of 0.1, which is similar to or better than opacity meters used at emissions inspection stations. The detection limit of improved versions is lower, so the sensitivity of the method is viewed as relatively low.

In an ionization chamber, ions created by radioactive decay are depleted by aerosol particles, with the signal – change in the ion current – being roughly proportional to the total particle length concentration, or relatively close to the lung-deposited surface area. The response is similar to the response of a diffusion charge based detector, albeit at lower sensitivity.

4.1.2 Technical description

Ionization chambers from commercially produced detectors (MHG 186, Lites, Liberec, Czech Republic; IIR-SLi, Icas, Prague, Czech Republic) all using ^{241}Am at 3–30 kBq. These were modified (reading analog output with a high input impedance circuit) and placed to sealed chambers, some in heated enclosures to avoid condensation. This allows for a relatively high controlled sample flow, allowing for fast response time. Electronics were improved to reduce drift and noise, and sample pump and sampling train were added. Prototype instruments, analogous to gas analyzers used in automotive inspection stations and repair facilities, were subjected to several experimental campaigns, where they have sampled exhaust gases or test aerosols along with reference instruments. Additional tests were done at automotive repair facilities where the instruments have sampled exhaust from vehicles with functional, defective or no diesel particle filters.

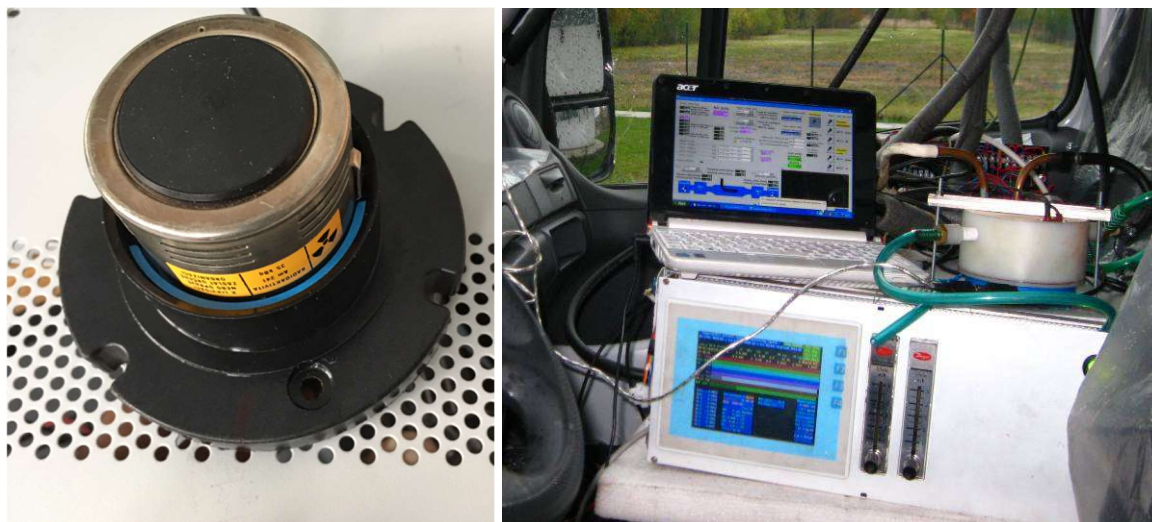


Figure 4-1: Ionization chamber (left) and prototype heated enclosure (right) placed on top of a portable emissions monitoring system

4.1.3 Validation

A review of previous laboratory tests of several heated enclosures housing an ionization chamber from an industrial smoke detector have been presented in the abstract, poster and presentation at the European Aerosol Conference, held in Gothenburg, Sweden, in August 2019 [3].

The overall experience suggests that detection limit varies from about 10^5 to 10^6 particles per cm^3 , or on the order of 1 ug/m^3 for nano-aerosols, even when raw, undiluted exhaust is sampled. The measured concentrations best correspond with the sum of electric mobility particle diameters (total particle length), with size-dependent correlation to the total particle number concentrations.

The instrument detection limit and ability to sample undiluted exhaust allow for detection of absent or grossly damaged diesel particle filters, representing majority of the “excess” emissions, but not small cracks and similar minor damage, and may allow for online indicative measurement of particle emissions on both gasoline and diesel engines. Tests with filtered exhaust did not show noticeable interference from gaseous pollutants.

In addition, tests were conducted with several smoke detectors, modified only by monitoring the analogue output signal, placed in a length of 75 mm diameter PVC wastewater pipe, through which a sample of exhaust was drawn through a diaphragm vacuum pump. The best unit performed adequately, except condensate was forming at higher engine loads, limiting its use to idle or high-speed idle of diesel engines, and the response time was reduced. At this condition, however, the unit was clearly able to detect an absent diesel particle filter.



Figure 4-2: Grey wastewater pipe with an ionization smoke detector inside

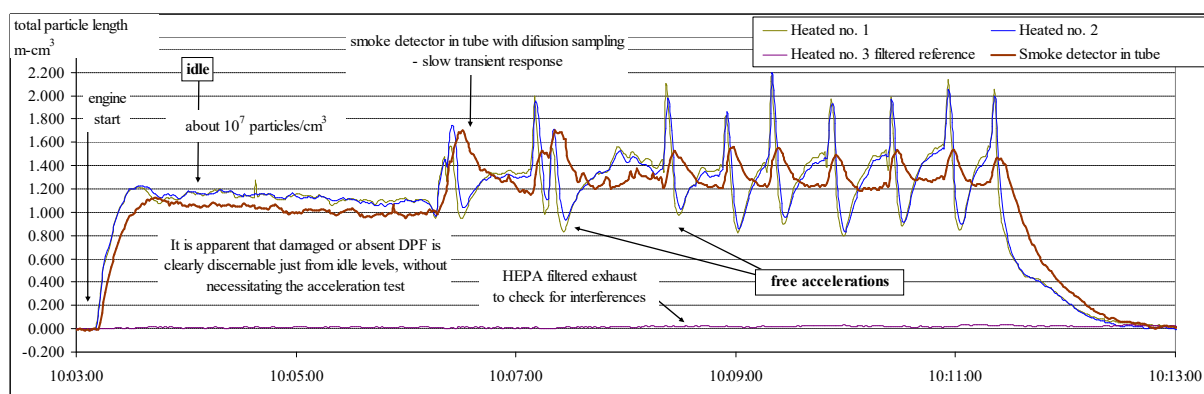


Figure 4-3: Comparison of a smoke detector in plastic tube (brown line) with two detectors in heated enclosures during a typical free acceleration smoke opacity test on a non-DPF car. The smoke detector in the tube has a considerably longer response to transient events, but retains its sensitivity to identify absence of DPF during idle test.

4.1.4 Applicability

Ionization type smoke detector, commonly sold in many countries for tens of EUR, with minor modifications, is capable of detecting absence or gross failure of a diesel particle filter when sampling engine exhaust at idle or at high idle.

The use of this sensor by uCARE can be at a car fair awareness campaign as a detector of malfunctioning PDFs (or DPF tampering) for individual cars. Alternatively, this tool can be used to demonstrate the pollution by multiple cars, e.g., near a kiss-and-ride in front of a school.

4.2 Miniaturized on-board device (Mini-PEMS)

The second instrument from the 'Mini-PEMS' solutions is the miniaturized on-board device (Mini-PEMS).

4.2.1 Target use of and design requirements

The envisioned use of the Mini-PEMS was monitoring of small engines, such as in mopeds, or garden machinery. While passenger car and heavy vehicle testing might be facilitated,

in addition to type approval PEMS, by SEMS or FTIR, Mini-PEMS appears to be the only alternative solution for small engine tests.

The envisioned targets were 10 kg mass and 10,000 EUR cost under a hypothetical mass production (not including engineering design and prototyping work), and based on all available information, they were generally met, although the final unit has not been built due to severe restrictions on international commerce, travel, and the capacity of the development team at the university laboratory.

4.2.2 Technical description

The design builds on a simple setup by Vojtisek-Lom and Cobb (University of Pittsburgh, 1996), where concentrations of gaseous pollutants – HC, CO, CO₂ and NO – are measured by “garage-grade” analysers used for nearly three decades in some regions of the United States for vehicle diagnostics, and exhaust flow is computed from engine intake mass air flow (MAF). MAF can be either measured directly or calculated using a “speed-density” method from engine displacement, engine rpm, temperature and pressure in the intake manifold, and volumetric efficiency. In many cases, the requisite parameters can be read online from the engine on-board diagnostics (OBD) interface using commercially available diagnostic tools.

This design was expanded by addition of an electrochemical sensor to measure NO₂, and by low-cost PM sensors using light scattering and/or measuring ionization chamber, as explained earlier. Also, sensors for measuring engine rpm and manifold intake pressure, two temperature sensors, a global positioning system (GPS) receiver, and a lithium ion (LiFeYPO) battery allowing for 3-4 hours of autonomous measurement have been added.

4.2.3 Validation

The validation is based on tests of two slightly larger units at the European Commission Joint Research Center. The tested units, validation tests and their results are described in a paper currently under review and public discussion in Atmospheric Measurement Techniques [4]. (Note: Czech national funding was used to support tests at the JRC.)

Additional validation has taken place during motorcycle tests carried by TNO (TNO Report 2017 R10565). Emissions from 14 mopeds and small motorcycles were measured in an emissions testing laboratory using a type approval test cycle appropriate for the respective individual mopeds. Measurements were done simultaneously by traditional laboratory instruments and by two earlier versions of the Mini-PEMS (larger but functionally equivalent). On the following graphs, mass emissions of HC, CO, NO, CO₂ and particulate matter, expressed as total mass (PM) and number of non-volatile particles (PN), is plotted, one point per test, with laboratory measurement on the horizontal axis and Mini-PEMS measurement on the vertical axis. A more detailed analysis revealed that the volumetric efficiency multiplier, much different for small engines than for automobiles, is the largest source of error. When correction is made using total fuel consumption per test (as measured by the laboratory), the Mini-PEMS and laboratory “fuel corrected” results are in general agreement for all measured gaseous pollutants, with particulate matter being subject to additional evaluation.

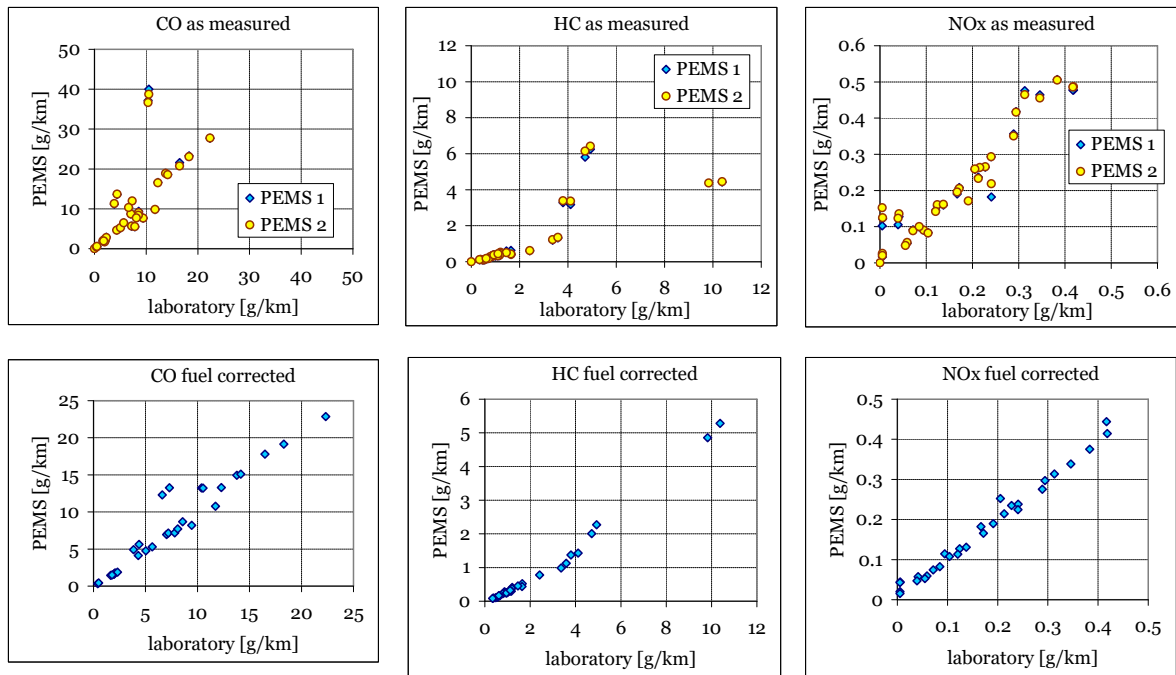


Figure 4-4: Validation of Mini-PEMS

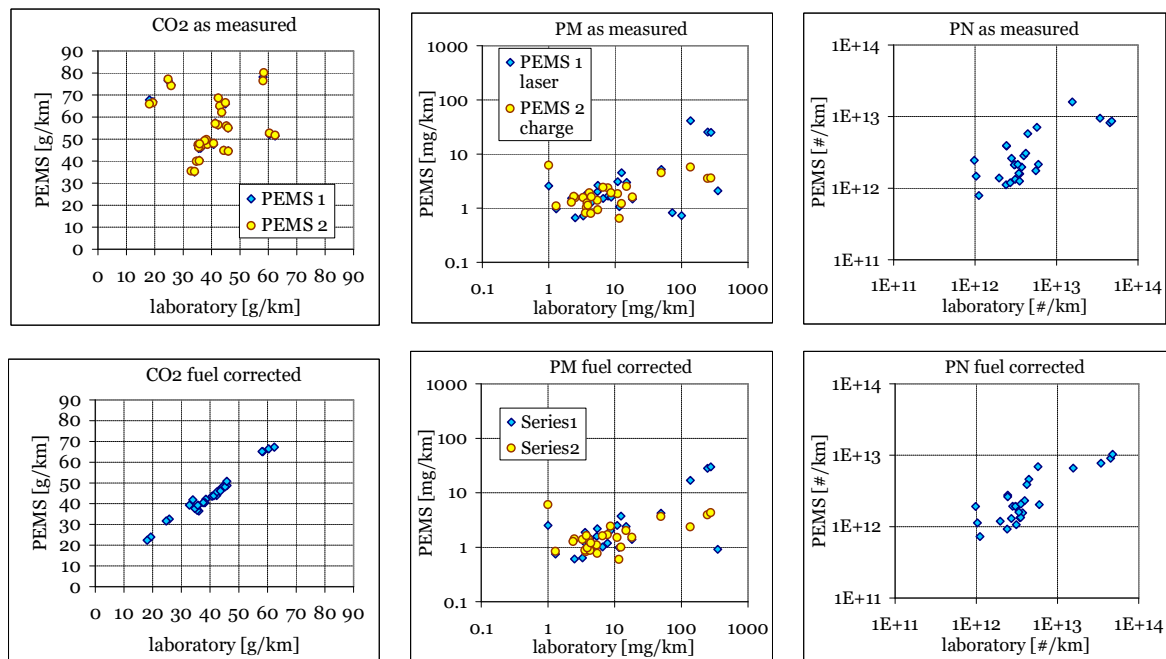


Figure 4-5: Validation of Mini-PEMS cont.

Added validation for NO₂ has been carried out on a Euro 5 automobile with a diesel engine with an oxidation catalyst during a real driving emissions test, where the Mini-PEMS has been compared with a type approval PEMS (Semtech Ecostar) during on-road operation of a Euro 5 diesel vehicle with an oxidation catalyst. It is apparent that while NO measurement of both units is in agreement, the response time of the added NO₂ electrochemical sensor is relatively slow.

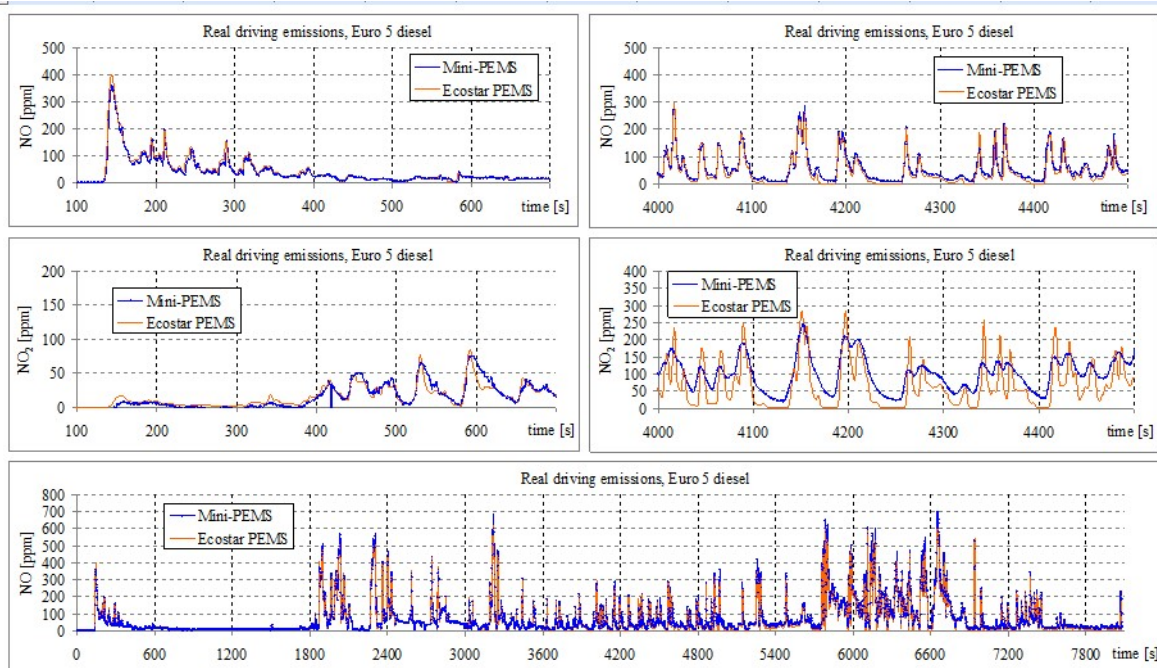


Figure 4-6: mini-PEMS validation against Ecostar PEMS

4.2.4 Applicability

The foreseen use by uCARE of the mini-PEMS is to establish the emissions of equipment used near people, for example a lawn-mower or other (small) combustion engine driven garden/agricultural equipment, builder/contractor equipment, etc.

One could think of a campaign to motivate replacement of combustion engine based equipment by electric equipment by showing the pollutant emissions of the combustion engine hedge trimmer/chain saw/etc. around the frequent user.

4.3 Portable FTIR

The third and final instrument from the 'Mini-PEMS' solutions group is the portable FTIR analyser. This instrument is the most expensive option, but the most versatile with highest accuracy.

4.3.1 Target use of and design requirements

With the deployment of NO_x aftertreatment technologies and advanced and alternative fuels, additional gaseous pollutants are worthy of consideration: potent greenhouse gases methane (CH₄, from methane based fuels) and nitrous oxide (N₂O, formed in NO_x aftertreatment devices); ammonia (NH₃) and potentially other reactive nitrogen species, produced in three-way catalysts and SCR systems; aldehydes associated with alcohol fuels. Most of the mentioned compounds, as well as all regulated compounds measured by type approval grade PEMS, can be measured with Fourier Transform Infra-Red (FTIR) analysers, commonly used for laboratory measurements of NH₃ concentrations in gas.

On-board Fourier Transform Infra-Red (FTIR) analysers are being proposed here as the universal tool for measurement of nearly all gaseous pollutants by a single instrument, capable of detecting all major heterogeneous molecules of concern – greenhouse gases CO₂, methane (CH₄), nitrous oxide (N₂O); reactive nitrogen species NO, NO₂, NH₃ and potentially hydrogen cyanide and isocyanic acid; emerging pollutants such as formaldehyde and higher aldehydes associated with alternative fuels. FTIR are generally expensive and large laboratory analysers. The target size, mass, power consumption and

cost are those comparable to type-approval PEMS: the instrument should fit in nearly all vehicles, the mass should be less than 50 kg, the power consumption in low hundreds of Watts, and the cost should be less than 100 000 EUR.

4.3.2 Technical description

Two pathways are suggested to exploit FTIR as a portable on-board instrument. In one, water is removed by cooling of the sample and/or selective membranes, after which greenhouse gases CO₂, CH₄, N₂O, and non-polar, non-water-soluble, highly volatile compounds such as NO and NO₂ can be readily quantified even at mediocre optical resolutions (units of cm⁻¹) and relatively short optical path lengths (on the order of 1 m), allowing small cells and detectors with thermoelectric cooling to be used.

For a more detailed and comprehensive analysis, water is kept in the sample, and the entire sampling train is heated to prevent condensation of water, ammonia, and other, less volatile, compounds. Retaining the water allows for the detection of additional compounds such as ammonia, formaldehyde, or ethanol. Higher optical resolution (0.5 cm⁻¹) is then typically required to resolve the compounds interfering with water and CO₂. Operating at a higher resolution, however, requires a faster detector and tighter tolerances in the optical path, and the increased noise needs to be balanced against the instrument response time. Another critical decision is the selection of the optical path length. Longer path lengths increase the instrument sensitivity, but also increase the occurrence of regions where analysis is prevented due to nearly complete attenuation by water, and typically require larger optical cell volumes, increasing the system response time. Optical path lengths of 2-10 meters have been used [5].

4.3.3 Validation

Three FTIR systems, all with liquid nitrogen cooled mercury cadmium telluride (MCT) detector, zinc selenide optics, optical resolution of 0.5 cm⁻¹, optical path length 5-6 m, and optical cell volume 200-400 cm³, already adapted for on-road use and used in the Czech Republic (Midac I-Series at the Technical University of Liberec, Nicolet Antaris IGS at the Czech Technical University in Prague, and Bruker Matrix at the Czech University of Life Sciences in Prague, all shown on photos below), were further evaluated. Detailed comparison testing was carried only for the MIDAC instrument for NO, NO₂, CO, CO₂ and later, in a limited extent, for NH₃, and to a lesser extent for the Nicolet (NO, NO₂, CO, CO₂). Additional desired comparisons were that for N₂O for all instruments, and a validation of the Bruker instrument.



Figure 4-7: FTIR instruments used on-road: MIDAC I-series, (left), Nicolet Antaris IGS (middle) and Bruker Matrix (right)



Figure 4-8: FTIR analyzers Nicolet(front) and MIDAC (back) in the cargo space of a 12-ton Euro VI diesel truck during an evaluation test at the Czech Technical University in Prague (3 steel ingots corresponding to approx. 50% payload are in the middle and batteries are in left front)

After early comparison tests of the Bruker instrument showing sample flow issues, the sample path and the sample flow rate was optimized. A lighter (albeit less durable) sample pump has been implemented to reduce the system mass.

Comparison tests with the Bruker instrument were carried out in January 2020 at the Technical University of Graz (TUG) and in February 2020 at the Vehicle Emissions Laboratories (VELA) at the European Commission Joint Research Center in Ispra, Italy. Comparison tests with the Nicolet instrument were carried out in March 2020 at the TUG.

The comparison tests at the TUG on a Euro VI heavy-duty truck show a general agreement among a type-approval PEMS (AVL MOVE), a laboratory FTIR (MKS 2030), and the portable FTIR (Bruker). An example of data (first part of chassis dynamometer version of the WHTC test no. 2611) is given below.

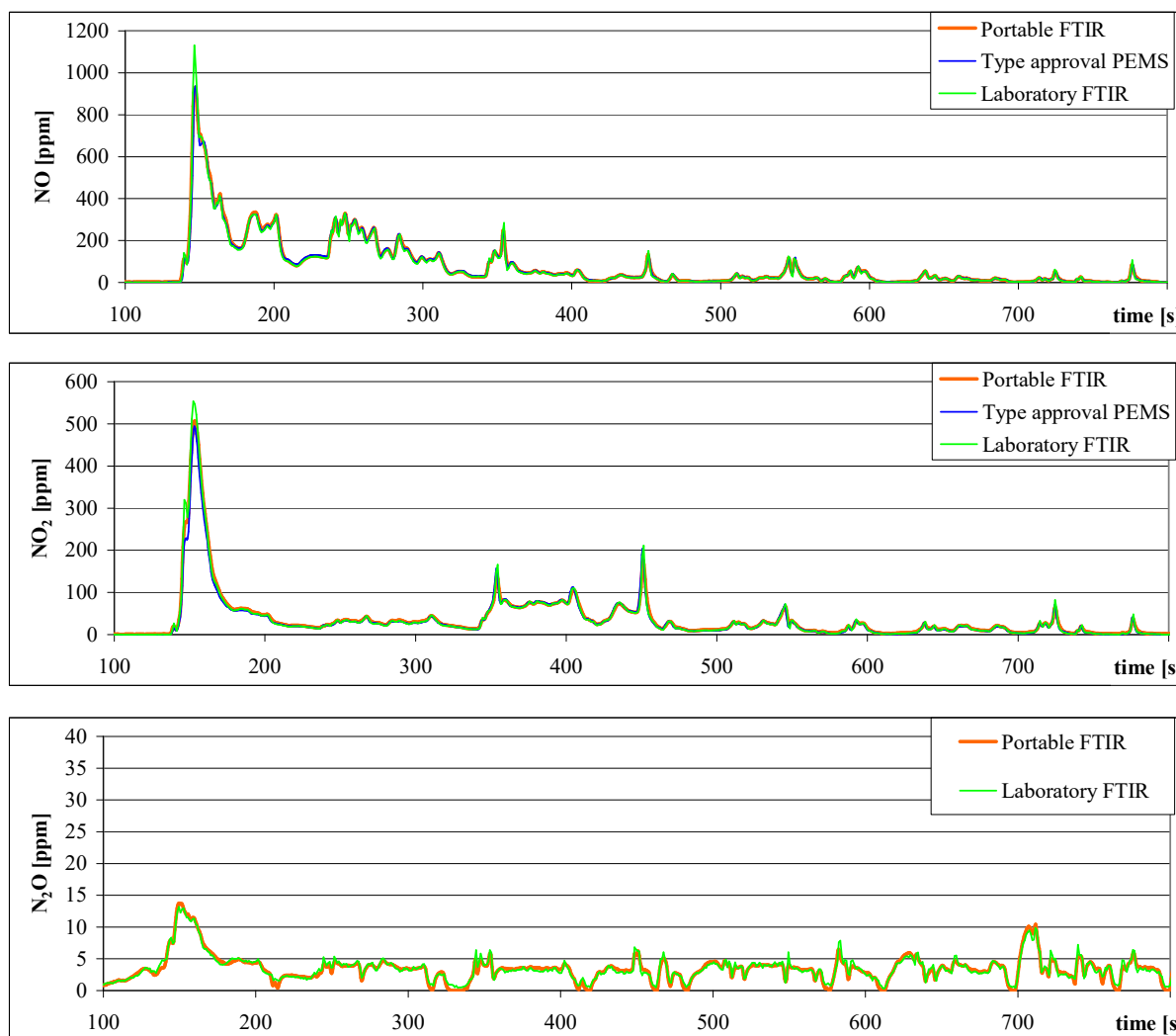


Figure 4-9: Validation of portable FTIR; compared to lab-grade equipment

The Nicolet testing took place immediately after the optical cell returning from a factory service. The instrument had calibration issues, which, due to the shutdown of the university laboratories to prevent the spread of the COVID-19, still remain to be resolved by collecting new calibration spectra, for the moment.

A demonstration of the Bruker system has sparked an initiative to use this FTIR in an impromptu chase vehicle study. The FTIR was installed into a Customs Office patrol van (about half a day procedure not requiring any modifications to the van) and used for a week to sample exhaust from trucks on the D1 motorway connecting Prague and Brno, with the goal to provide at least a rough estimate of the portion of the trucks using SCR emulators, devices that simulate a proper function of the SCR catalyst to the engine control unit, while the injection of the reducing agent (AdBlue, Diesel Exhaust Fluid) is disabled.

The tests were remarkably successful and are described in a manuscript currently under a review for possible publication in the Science of the Total Environment journal.

4.3.4 Applicability

This solution could be used by uCARE in a fairground pilot, for example in an event where alternative fuels are being promoted, to create awareness of the emissions of these alternative fuels. Concerning are both usual emissions such as CO₂, N₂O, NO, NO₂ and less

usual emissions such as methane (CH_4), Ammonia (NH_3), hydrogen cyanide and aldehydes. Of course, this is only one of many possible use-cases.

5 Conclusions and recommendations

Though some equipment for use in pilots as envisaged by uCARe are available, the high costs and limited availability of these solutions triggered the development of additional cheap and simple solutions.

Three paths were defined and solutions were delivered:

1. A device to extract data and signals from the CAN and/or directly from the OEM sensors: NO_x feedback tool.
2. A device that makes use of installed (non-OEM) sensors to measure and use the emission concentration: Crosssyn sensor data logger.
3. A 'mini-PEMS' consisting of cheap testing solutions to measure different components, incl. non-regulated emissions: Particle sensor, Mini-PEMS and portable FTIR.

The NO_x feedback tool provides drivers insight into the real-time NO_x emission of their vehicle. It is suitable for Euro 6 Diesel vehicles, from which it reads out the NO_x sensor data. Validation tests show strong correlation between NO_x emissions and LEDs panel feedback. This device is suited for looking into driving behaviour and how it changes when giving feedback on the NO_x emission.

The Crosssyn system's purpose is to log the data received from both OBD and installed sensors. Validation shows that the system is capable of correctly communicating with a UNINOX NO_x/O₂ sensor. It is made for vehicles with OBD. This device is suited for collecting vehicle emission data and analysing this. This in turn could be used for providing feedback to the driver after each drive.

The Particle sensor, Mini-PEMS and the portable FTIR are all part of the third path. The particle sensor uses parts of a cheap smoke detector. Validation shows that the system is capable of detecting a severely damaged DPF as well as a removed DPF. This device is suited for doing parking lot experiments, for example checking if a vehicle has a removed or highly damaged DPF.

The Mini-PEMS and laboratory results are in general agreement for all measured gaseous pollutants, with particulate matter being subject to additional evaluation. It is cut out for vehicles with small engines, e.g., mopeds. This device is suited for analysing the pollutant and poisonous emissions of equipment used nearby people.

The portable FTIR is proposed as a universal tool for measurement of nearly all gaseous pollutants by a single instrument. Validation shows a general agreement among a type-approval PEMS (AVL MOVE) and a laboratory FTIR (MKS 2030). It is useful as an alternative to PEMS. This device is suited for analysing the gaseous emissions of any vehicle using only one piece of equipment.

These tools are developed especially to be used in pilots and campaigns. Their purpose is accomplishing great results without a large budget. The tools are there to inspire and provide means for creating WP3 pilots and campaigns. Numerous possibilities can be conceptualized: providing feedback to drivers and improving their driving style, parking lot testing vehicles on their (particle) emissions, testing the emissions of combustion engine based equipment that is commonly used near people, etc.

We recommend using these tools in pilots and campaigns, either within the uCARe projector outside of this project, to increase the awareness of pollutant emissions, give a more clear insight into the sources and stimulate reducing these emissions.

References

- [1] Vermeulen et al., "SEMS operating as a proven system for screening real-world NOx and NH3 emissions," TAP paper 58, 20th International Transport and Air Pollution Conference 2014, Graz.
- [2] AutoPi.io ApS, [Online]. Available: <https://www.autopi.io/>. [Accessed April 2020].
- [3] Vojtisek-Lom, M., et al., "Ionization Smoke Detector Based Tool for Particle Number Measurement: Detection of Defective Diesel Particle Filters and of Nanoparticles in Workplace," Presentation at the European Aerosol Conference, 2019.
- [4] Vojtisek-Lom, M., et al., "A miniature Portable Emissions Measurement System (PEMS) for real-driving monitoring of motorcycles.," Atmos. Meas. Tech. manuscript no. amt-2019-387.
- [5] Vojtisek-Lom et al., "Portable, on-board FTIR spectrometers: A universal tool for real-world monitoring of greenhouse gases, reactive nitrogen compounds, and other gaseous pollutants?," Abstract submitted to the Transport and Air Pollution conference, to be held in Graz, Austria, September 2020.

Annex A: NOx indicator building instructions

Parts list

Table A-1: NOx tool parts list

Part	Part no.	Estimated price 1 pcs (ex VAT)
MikroE Flip 'n Click (32-bit SAM3X)	MIKROE 1984	EUR 42
MikroE CAN SPI Click 3.3V	MIKROE 986	EUR 20
Seeed 10 RGB LED bar	WS 2813	EUR 5
Kvaser OBD cable	73-30130-00723-9	EUR 50
Seeed 4-wire cables	110990038	EUR 4
2x SUB-D 9 pin male		EUR 1
1x SUB-D 9 pin female		EUR 1
5.5mm jack pin		
Bud casing	PN-1323-C	EUR 13
Black wire (20 AWG)		
Red wire (20 AWG)		
Yellow wire (23 AWG)		
Green wire (23 AWG)		
4 spacing studs		
Velcro tape		
3mm heat shrink		

Principle of OBD requests

The NOx sensor information reading will be based on either ISO 15031 or ISO 27145 OBD requests, using SAE J1979 PID's:

- Service 0x01 – current data (ISO 15031)
- Alternatively Service 0x22 – current data (ISO 27145)
- PID 0x83 – NOx sensor data
 - Byte A: available sensors (binary)
 - Byte B+C: NOx_1
 - Byte D+E: NOx_2 (only if available)

Building instructions

Casing

- Prepare the casing by drilling / filing holes to fit 1 female SUB-D connector on 1 side, and 1 male SUB-D connector on the opposite side.

Microcontroller

- Mount the CAN SPI Click shield on location A of the Flip 'n Click. This slot will provide for the power and SPI communication with the on-board MCP2515 CAN chip.
- Cut a red and black wire on approximately 10 cm and strip them. Solder a red wire to the centre of the 5.5mm jack, and a black wire to the shield of the 5.5mm pin.

OBD cable

- Solder the red, black, yellow and green wire to the SUB-D female connector that is fitted on the casing. This will be the receptable plug for the OBD cable. A schematic can be found below.

Note: In this example, a Kvaser OBD cable is used to connect the NO_x indicator to the vehicle. If you prefer to use a different (perhaps cheaper) cable, make sure to adapt the wiring from the SUB-D connector on your casing to the micro controller to match these criteria.

Table A-2: OBD pin-out

Signal	OBD-pin	SUB-D connector pin Kvaser OBD	NO _x indicator connection
Battery 12V	16		5.5mm jack center
Chassis ground	4		5.5mm jack shield
CAN high	6		CAN SPI Click "H" terminal
CAN low	14		CAN SPI Click "L" terminal

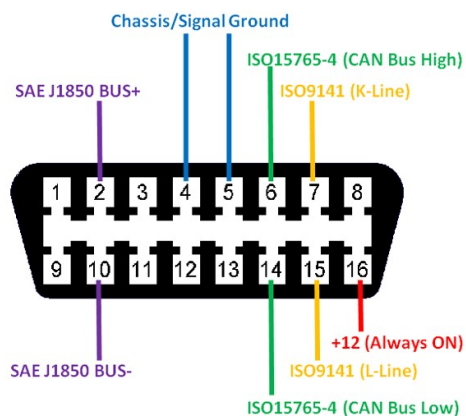


Figure A-1: OBD pin-out

LED bar

- From the microcontroller to the male SUB-D connector on the casing, 3 cables are needed to provide the LED bar of power and data. A schematic can be found below.
- Solder 2x 50cm SEEED 4-wire cables together, to get 1 cable of a meter in length. This will gap the distance between the LED bar in your aircon outlet to the casing somewhere on the floor.
- Cut one end of the SEEED cable, and solder the colours to the correct pins on a SUB-D female connector.

Note: apply heat shrink pieces before soldering, so the 3 wires are independently isolated.

Table A-3: Flip 'n Click pin-out

Flip 'n Click position B pin	SUB-D male connector on casing pin	SUB-D female connector to LED	Function
+5VDC	1	1: Red	Power
GND	2	2: Black	Ground
	6	6: Yellow	Data

Code

- Flashing code to the micro controller is done via a general micro USB cable. The code provided for this project is a binary BIN-file. This is compiled software, that can be flashed to the controller via a free software program like Bossa from Shumatec via an easy-to-use GUI. You can download the software from their website.
- The code contains the following functionalities:
 - When NO_x sensors of vehicle are not ready (cold start), one LED will blink to notify the driver of this period
 - The LED will scale automatically to the NO_x emission levels of the vehicle
 - The software automatically detects the correct ISO protocol for OBD requests